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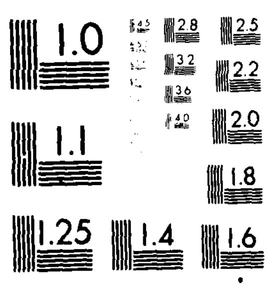

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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT ON THE SHIP VARIABLES EXPERIMENT: THE EFFECT OF SHIP CHARACTERISTICS AND RELATED VARIABLES ON PILOTING PERFORMANCE

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November 1981

Interim Report

Prepared for

U.S. Department of Transportation
United States Coast Guard
Office of Research and Development
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16. Abstract

The experiment described here is one of a series done for the U.S. Coast Guard to quantify the relationship between variables related to aids to navigation and piloting performance in narrow channels and, potentially, safety in such channels. This is one of several experiments restricted to visual piloting, and further to buoys only. It was done on a simulator built for the U.S. Coast Guard at Eclectech Associates in North Stonington, Connecticut. The variables evaluated were:

Ship Characteristics: an 80,000 dwt tanker with a rear bridge and an 80-foot height of eye versus a 30,000 dwt tanker with a midship bridge and a 45-foot height of eye

Size and Complexity of Bow Image: larger and smaller bow image for the 30,000 dwt tanker

Speed of transit: 6 knots versus 10 knots

Buoy density: a three-buoy turn and short (5/8 nm) spaced, gated buoys versus a one-buoy turn and long (1-1/4 nm) spaced, staggered buoys

Underkeel clearance: 1 foot versus 600 feet

Only selected combinations of these variables were included as scenarios in the experiment. Tasks and wind and current effects were varied within the scenarios. The findings are presented as the means and standard deviations of crosstrack position of →

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16. Abstract (cont)

transits under each condition. Observed differences in piloted performance with the two ships are related to differences in their inherent controllability parameters to provide a methodology for extrapolating the findings to a variety of ships not included in the experiment.

17. Key Words (cont)

buoy placement, controllability, inherent controllability, piloted controllability

PREFACE

The experiment described here is a component of the United States Coast Guard's Performance of Aids to Navigation Systems project. This project is meant to collect the data necessary to lead to guidelines for the design of AN Systems. The project includes (or will include) a survey of U.S. ports to summarize existing conditions; a survey of relevant variables to be considered; a major simulator experiment in visual piloting done at Maritime Administration's Computer Aided Operations Research Facility (CAORF) in New York; four visual piloting (SRAN) and three radio aids piloting (RA) experiments done at a simulator developed for the project at Eclectech Associates, Inc., in North Stonington, Connecticut; and an at sea data collection to provide validation of the USCG/EA simulator and the experimental results. The final step will be the preparation of the overall findings for the development of design guidelines.

The experiment described here is the second of four visual piloting experiments done on the USCG/EA simulator. Visual aids in this experiment will again be restricted to large lighted buoys. This experiment evaluates the effects of ship variables in isolation and in combination with environmental conditions, piloting tasks, and density of buoy information. The following is a summary of conclusions supported by the experiments.

- The larger (80,000 dwt) ship shows increases in crosstrack variability over that of the smaller (30,000 dwt) on the order of 60 to 90 percent for various tasks. These include: trackkeeping with a following wind and current, negotiating a 35 degree turn, maneuvering to the channel centerline with a crosswind and crosscurrent, and trackkeeping with a crosswind and crosscurrent.

- Increase in piloted crosstrack variability for the 80,000 dwt ship is approximately 1 - 1/2 times the increase in turn response (as measured in the distance domain) and track response variables versus these variables for the 30,000 dwt ship. This relationship suggests a methodology for extrapolating to new ships.

- While piloted performance with the 30,000 dwt ship can be improved from adequate to precise with additional buoys, performance with the 80,000 dwt ship needs a high level of buoy density for merely adequate performance.

- Only turn rate variables are affected by speed; and then only when expressed as time, not as distance.

- Piloted performance during maneuvering is not time-dependent, but distance-dependent. During maneuvering the pilot needs adequate and frequent indications of his crosstrack and alongtrack positions.

- For maneuvers through turns equal to or less than 35 degrees, smaller underkeel clearance may have a beneficial effect. Through greater turns, the small clearance may have a detrimental effect.

- Performance on the CAORF and USCG/EA simulators is the same, not only in relative differences among conditions; but also in absolute magnitude of effects for conditons simulated.

ACKNOWLEDGEMENTS

The authors would like to again thank CAPT. J.T. Montonge of the United States Coast Guard for his contributions to, and support of, the project. We would also like to thank CDR John R. Roeber and LT John Anthony for their participation. We are again grateful to Mr. Karl Schroeder for his continuing help.

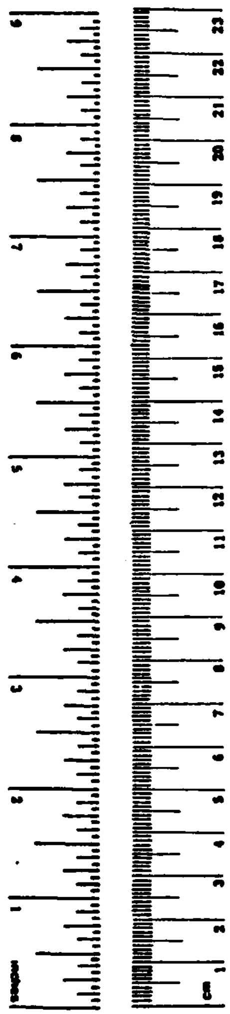
The authors would like to again inpress their appreciation to CAPT. David G. Leonard, President of Northeast Maine Pilots, Inc., for his, and for his association's, continuing cooperation. We want to thank CAPT. Kenneth Warner for his suggestions during the presimulation runs. We want to thank the other members of the association who served as experimental subjects and made valuable comments on the simulation and on the piloting process as it contributed to the experimental findings.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

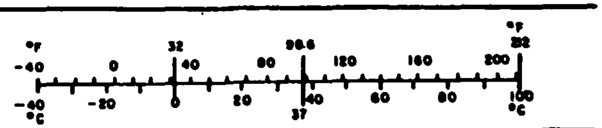
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

INTRODUCTION

This experiment contributes to the United States Coast Guard's Performance of Aids to Navigation Systems Program, which is meant to establish system design guidelines for U.S. ports. It is one in a series of simulator experiments methodically evaluating the effects of variables expected to affect visual piloting in restricted waterways. Earlier experiments in the series emphasized variation in the placement of aids to navigation (buoys) with a constant ship. This experiment evaluates the effects of ship characteristics in isolation and in combination with environmental conditions, piloting tasks, and density of buoy information. While only two different ships were used in this experiment, the findings are used to develop a methodology for extrapolation to a variety of ships.

A previous simulator experiment in the series was done at CAORF, the Maritime Administration's Computer Aided Operations Research Facility at Kings Point, New York. Other experiments, including the present one, were done at a simulator built for the U.S. Coast Guard project by Eclectech Associates, Incorporated in North Stonington, Connecticut. The use of data from two simulators and from several experiments both necessitates and allows a continuous evaluation of similarities and differences between the simulators and among the experiments.

The primary purpose of this experiment is the evaluation of the effect on piloting performance of the following variables:

- Ship characteristics: an 80,000 dwt tanker with an aft wheelhouse and an 80-foot height of eye versus a 30,000 dwt tanker with a midship wheelhouse and a 45-foot height of eye
- Speed of transit: 6 knots versus 10 knots
- Buoy density: a three-buoy turn and short (5/8 nm) spaced, gated buoys versus a one-buoy turn and long (1-1/4 nm) spaced, staggered buoys

Differences in piloted performance over these variables are related to differences in inherent controllability characteristics to provide a methodology for extrapolating the findings to a variety of ships and conditions not included in the experiment.

A secondary purpose is an evaluation of an additional variable:

- Size and complexity of bow image: larger and smaller bow image for the 30,000 dwt tanker

RELATIVE DEPENDENCE ON BUOY DENSITY WITH THE TWO SHIPS

Piloting performance with high and low buoy density was compared for the 30,000 and 80,000 dwt tanker for a variety of piloting situations:

- Entrance to the channel: the 80,000 dwt tanker, more than the 30,000 dwt tanker, needed a high density of gated buoys to safely enter the channel and maneuver to the centerline.
- Turn recovery: the 80,000 dwt tanker more than the 30,000 dwt tanker needed three turn buoys and a high density of gated buoys to recover from a 35-degree turn in a new channel.

- Trackkeeping with crosswind and crosscurrent: the 30,000 dwt tanker performed better with a high density of gated buoys than with low. Handling the 80,000 dwt tanker in a crosswind and crosscurrent is a problem that is not solved with high buoy density.

In terms of aids to navigation system design:

For a variety of piloting tasks, the pilot is best served by a gate ahead that gives him a certainty of short-term destination. While piloting performance with the 30,000 dwt tanker can be improved from adequate to precise with additional buoys, performance with the 80,000 dwt tanker needs a high level of buoy density for merely adequate performance in entering a channel, exiting a turn, or trackkeeping with crosswind and crosscurrent.

In terms of the piloting task:

The beneficial effect of higher buoy density is not as great as the detrimental effect of larger ship size.

DIFFERENCES IN PILOTING PERFORMANCE WITH THE TWO SHIPS

Piloted performance differences between the 30,000 dwt tanker and the 80,000 dwt tanker, both run under conditions of high buoy density, or "perfect information," are presumably wholly due to differences in the inherent controllability and in the physical dimensions and design of the two vessels. Differences in performance appeared for a number of piloting tasks in the scenario. Generally, performance was poorer with the 80,000 dwt tanker.

- Trackkeeping with a following wind and following current: the 80,000 dwt tanker showed less precise performance than the 30,000 dwt tanker.
- The turn: the 80,000 dwt tanker initiated the turn late and took longer to maneuver, resulting in an overshoot in the new leg compared to the 30,000 dwt tanker.
- Maneuvering to the centerline with a crosswind and crosscurrent: the 80,000 dwt tanker reached the centerline sooner, but with a considerably greater crosstrack variability than the 30,000 dwt tanker.
- Trackkeeping with a crosswind and crosscurrent: the 80,000 dwt tanker showed less precise performance than the 30,000 dwt tanker.

To summarize piloted performance differences attributable to differences in inherent controllability of the two ships:

The 80,000 dwt tanker showed increases in crosstrack variability over that of the 30,000 dwt tanker on the order of 60 to 90 percent for various tasks in the scenario.

A METHODOLOGY TO EXTRAPOLATE THE FINDINGS TO OTHER SHIPS

It was the purpose of this experiment to relate differences between the two ships in piloted performance to differences in their inherent controllability characteristics. To this end, computer simulations (without a pilot) were run of sea trial maneuvers for the two experimental ships. For each ship, the 30,000 dwt and the 80,000 dwt tanker, turning circles and 20/20 Z maneuvers were run at 6 knots with a 1-foot underkeel clearance. (See Appendix A for definition of maneuvers and response variables).

For turning circles, the tactical diameter, the advance, and the transfer were essentially the same for the two ships. Therefore, the turning circles do not appear to be predictive of piloted performance with varying ship size.

For the Z maneuver, heading response variables were essentially the same for the two ships, but turn response and track response variables differed: the 80,000 dwt tanker showed slower turn response and more crosstrack displacements. It was concluded that these variables are predictive of piloted performance differences.

The increase in piloted crosstrack variability for the 80,000 dwt tanker is approximately 1-1/2 times the increase in turn response (as measured in the distance domain) and track response variables versus these variables for the 30,000 dwt tanker.

This generalization suggests a methodology for extrapolating to new ships:

Piloted performance as a function of ship size is potentially predictable from measures of inherent controllability.

THE EFFECT OF SHIP SPEED ON PILOTED PERFORMANCE AND INHERENT CONTROLLABILITY

It had been hypothesized that increased speed (from 6 to 10 knots) would improve piloted performance. This was not the case. For maneuvering portions of the scenario, speed actually worsened performance for the 80,000 dwt tanker. The only improvement was a slight one while trackkeeping with crosswind and crosscurrent. In terms of aids to navigation systems design and operations standards:

Large ships transiting narrow channels do best with high buoy density and low speeds.

Computer simulation runs were made for the two ships at two speeds (6 and 10 knots). It was found that only turn rate variables were affected by the change in speed and then, only when expressed as time. When turn rate was converted into alongtrack distance, speed did not have an effect on this variable. Each ship followed the same track for its Z maneuver whatever the speed. At a faster speed it went along this track faster.

Is it the time or the alongtrack distance needed by the ship for a maneuver that is important in piloting? To answer this question, a simulator comparison was made between the 30,000 dwt tanker at 6 knots and the 80,000 dwt tanker at 10 knots. Under these conditions, the ships maneuver in the same time, but still differ in the alongtrack distance needed. The piloted performance for the two ships under these conditions was also compared. Generally, the piloted performance differences observed when both ships were run at 6 knots were maintained. Therefore:

Piloted performance during maneuvering is not time-dependent, but distance-dependent.

As a generalization relevant to both aids to navigation channel design and an understanding of the piloting tasks:

During trackkeeping, the pilot needs adequate and frequent indications of crosstrack position.

During turning and maneuvering, the pilot needs adequate and timely indication of both crosstrack and alongtrack position.

THE EFFECT OF UNDERKEEL CLEARANCE ON INHERENT CONTROLLABILITY

Computer simulations were run for the two ships with 1-foot and 600-foot underkeel clearance. For the turning circles, the smaller clearance had a detrimental effect on all variables. For the Z maneuvers, the smaller clearance had a small but beneficial effect. These results predict for future research that:

For maneuvers through turns equal to or less than 35 degrees, smaller underkeel clearance may have a beneficial effect.

For maneuvers through turns greater than 35 degrees, smaller underkeel clearance may have a detrimental effect.

SIMULATION EFFECTS AND THEIR GENERALIZATION TO REAL WORLD PILOTING

1.) Bow Image. Two different bow images had been used for the 30,000 dwt tanker in earlier experiments: a larger, more complex bow at CAORF and a smaller, simpler bow on the USCG/EA simulator for the Channel Width experiment. These were compared in this experiment. There was an advantage for the larger, more complex bow with a following wind and following current, but not with a crosswind and crosscurrent. To interpret this finding in terms of the piloting process:

> *With a symmetrical orientation to the channel edge marked by buoys, the pilot is better able to make relative judgments of his distance to the edges with a large bow that comes closer to those edges.*

2.) Comparison Between Performance on the CAORF and USCG/EA simulator. Earlier in the project a comparison was made between performance on the CAORF and the USCG/EA simulators. For the Channel Width experiment, it was found that the relative differences among conditions were the same for both simulators, but the absolute magnitude of crosstrack variability was larger overall for the USCG/EA simulator. It was suggested that one possible reason for this difference in performance was a difference in wind functions: at USCG/EA, the crosswind had a 13-degree greater variation in direction. In the present experiment the wind was more similar to that at CAORF. As a result:

Performance on the CAORF and USCG/EA simulators is the same, not only in relative differences among conditions, but also in absolute magnitude of effects for the conditions simulated.

Section 1
INTRODUCTION

1.1 AN OVERVIEW OF THE AIDS TO NAVIGATION PROJECT

The United States Coast Guard is responsible for safety in U.S. harbors and channels and, therefore, for the aids to navigation (AN) necessary to ensure that safety. It is in fulfillment of this responsibility that the Coast Guard is sponsoring a simulator-based program of research into the performance of aids to navigation systems. Their interests include visual aids to navigation, radar, and radio aids. The final objectives of the project are the use of experimental data to derive design criteria for the placement of aids to navigation and to specify radio aids to navigation systems for narrow channels with turns. Completed components of the project are available as separate reports. The first of these was an analysis of the variables expected to affect visual piloting.[1] To enhance the applicability of the findings to real-world harbors, a survey of major U.S. ports was done from charts, cataloging the conditions that exist.[2] Two experiments on visual piloting with floating aids have been completed. These are referred to frequently in this paper as the "CAORF"[3] and "Channel Width"[4] experiments. The planning of the present experiment is available and is referred to here as the "Ship Variables Presimulation Report."[5] Several related studies on radio aid piloting are also complete.[6, 7, 8]

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[1] W.R. Bertsche and R.C. Cook. "Analysis of Visual Navigational Variables and Interactions, Interim Report. U.S. Coast Guard, Washington, D.C., October 1979.

[2] W.R. Bertsche and R.T. Mercer. "Aids to Navigation Configurations and the Physical Characteristics of Waterways in 32 Major U. S. Ports" U. S. Coast Guard, Washington, D. C., October 1979.

[3] M.W. Smith and W.R. Bertsche. "Aids to Navigation Report on the CAORF Experiment. The Performance of Visual Aids to Navigation as Evaluated by Simulation." U. S. Coast Guard, Washington, D.C., August 1980.

[4] M.W. Smith and W.R. Bertsche. "Aids to Navigation Principal Findings Report on the Channel Width Experiment: The Effects of Channel Width and Related Variables on Piloting Performance." U.S. Coast Guard, Washington, D.C., January 1981.

[5] D. Atkins. "Evaluation of Ship Variables and Visual Information Flow on Accuracy of Shiphandling in a Buoyed Channel (Ship Variable Experiment)." U.S. Coast Guard, Washington, D.C., December 1980.

[6] R.B. Cooper and K.L. Marino. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays - The Miniexperiment." U.S. Coast Guard, Washington, D.C., September 1980.

[7] R. B. Cooper, K. L. Marino, and W. R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-1 Experiment." U. S. Coast Guard, Washington, D. C. January 1981.

[8] R.B. Cooper, K.L. Marino, and W.R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, The RA-2 Experiment." U.S. Coast Guard, Washington, D.C., April 1981.

The first simulator experiment on floating aids to navigation was conducted at CAORF, the Maritime Administration's Computer Aided Operations Research Facility in New York. Later ones, including the one to be described here, were conducted at a simulator built for this U.S. Coast Guard project by Eclectech Associates in North Stonington, Connecticut. Both are bridge simulators, which provide the bridge, the ship hydrodynamics, the environmental effects, and the visual scene necessary for this series of experiments. A comparison of the results obtained on the two is discussed in the Channel Width report. The simulation results of the present experiment are compared to earlier results in Section 3 of the present paper.

The performance of aids to navigation, and of pilots using aids to navigation, is the result of a complex process under the control of many variables. The 15 variables of interest in the project are listed in Table 1. There are more variables than can be included in a single experiment. Instead, a systems approach which evaluates a part of the process at a time is necessary. The subsets of the relevant variables selected for the first visual experiments are indicated in the table. The emphasis in the first experiments was on varying the conditions that control the amount of visual information buoys provide to the pilot. The visual conditions provided were combined with a complex scenario that required performance in both trackkeeping and maneuvering, with and without perturbations. A single ship was used for all conditions in both experiments. It was a 30,000 dwt tanker with relatively difficult maneuvering characteristics for its size and type, moving at a relatively slow speed of 6 knots through the most difficult maneuvering portion of the scenario. The general finding of the experiments was a relationship between the

TABLE 1. NAVIGATION PROCESS VARIABLES

VARIABLE	EXPERIMENT
Ship	
Perspective view	Ship
Speed	Ship
Maneuverability	Ship
Channel dimensions	
Banks	
Width	Channel Width
Turn angle	CAORF
Turn radius (configuration)	CAORF
Environmental factors	
Current/wind	CAORF, Channel Width, Ship
Day/night	CAORF
Visibility/detection distance	CAORF
Traffic ships	CAORF
AN placement	
Spacing	CAORF, Channel Width, Ship
Straight channel marking	CAORF, Channel Width, Ship
Flash period	
Turnmarking	CAORF, Ship

maneuvering and/or perturbation requirements of the scenario and the reliance on visual information: when maneuvering was difficult, the pilot's performance was most dependent on the buoy characteristics.

The relationship between maneuvering requirements and dependence on visual information suggests that the ship's characteristics may be critical variables in the design of visual aids to navigation systems. An understanding of these variables is necessary for accommodating the conclusions from earlier experiments to the requirements of a variety of ships. *Is the best aid to navigation system for a channel the best for all ships? Or must the system be adapted to the characteristics of the most frequent or most demanding ship that uses that channel or port?* To answer this question, two different ships were run at two speeds and under two conditions of visual information density. These conditions constitute the present experiment.

1.2 THE EXPERIMENTAL CONDITIONS FOR THE SHIP VARIABLES EXPERIMENT

The primary purpose of this experiment is the evaluation of the effect on piloting performance of the following variables: ship characteristics, speed of transit, and amount of information provided by the aid to navigation system. A secondary purpose is a comparison of performance using different bow images. Not all combinations generated by these variables were run. The simulation was limited to those combinations, or scenarios, outlined in Figure 1. These scenarios allow the comparisons outlined in Table 2.

1. The Effect of Bow Image. Scenario 1 was run with a relatively small bow image on the front screen and no bridge wings. This was a repetition of the Channel Width experiment conditions. Scenario 2 had a larger bow image and simulated

TABLE 2. THE AVAILABLE COMPARISONS BY SCENARIO NUMBER

VARIABLE	SCENARIO
THE EFFECT OF BOW IMAGE	
Small versus large bow	1 versus 2
THE EFFECTS OF SHIP CHARACTERISTICS AND INFORMATION DENSITY	
Low versus high information density (30,000 dwt ship)	2 versus 5
Low versus high information density (80,000 dwt ship)	6 versus 7
30,000 versus 80,000 dwt ship (low information density)	2 versus 6
30,000 versus 80,000 dwt ship (high information density)	5 versus 7
THE EFFECTS OF SHIP CHARACTERISTICS AND SPEED	
Six versus 10 knots (30,000 dwt ship)	2 versus 3
Six versus 10 knots (80,000 dwt ship)	6 versus 8
30,000 versus 80,000 dwt ship (6 knots)	2 versus 6
30,000 versus 80,000 dwt ship (10 knots)	3 versus 8
THE EFFECT OF SHIP SIZE (EQUAL TURNING RESPONSE)	2 versus 8

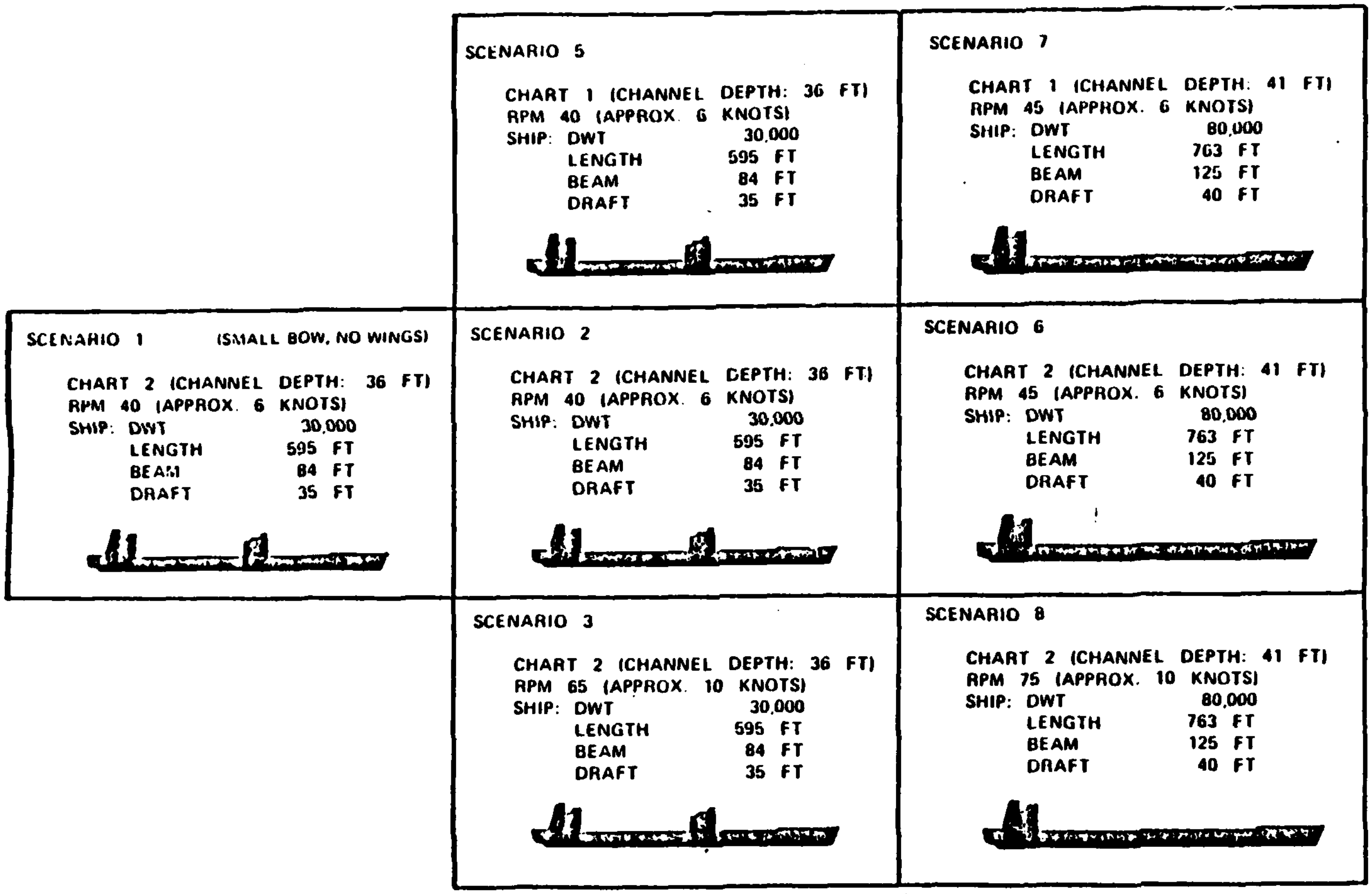


Figure 1. The Seven Experimental Conditions

bridge wings. It was meant to represent the CAORF conditions. These bow images are described in Appendix A.

2. The Effects of Ship Characteristics and Information Density. Scenarios 2 and 5 were run with a 30,000 dwt tanker with a midship bridge and a 45 foot height of eye. This is the ship used in the earlier experiments. (It has the two bow images in 1.) Scenarios 6 and 7 were run with an 80,000 dwt tanker with a rear bridge and an 80 foot height of eye. This ship is new in this project. The physical and performance characteristics of the two ships used are described in detail in Appendices A and B. Each ship was run under two conditions of visual information. Scenarios 5 and 7 contained a high level of information. Earlier experiments identified gates, 5/8 nm spacing, and three buoys in the turn as the favorable conditions. This combination was labeled Chart 1 and is illustrated in Figure 2. Scenarios 2 and 6 were run with a low level of visual information, comprised of the unfavorable conditions: staggered buoys, 1-1/4 nm spacing and one buoy in the turn. This combination was labeled Chart 2 and is illustrated in Figure 3.

3. The Effects of Ship Characteristics and Speed. All the scenarios described above were run at a speed of 6 knots through the water. Scenarios 2 and 6, the 30,000 and 80,000 dwt ships run with low information density conditions, were matched by two additional scenarios, 3 and 8, run at a speed of 10 knots through the water. This higher speed is new for this series of experiments. Ship performance differences as a function of speed are discussed in Appendices A and B.

1.3 CONDITIONS CONSTANT TO ALL SCENARIOS

The experimental comparisons of interest are made in a context of appropriate constant conditions. It should be emphasized that the comparisons among the experimental conditions are specific to the constant conditions and might not show the same differences if the constant conditions were changed. For this reason, it is necessary to use the same care in the selection of the constant conditions as in the selection of the experimental conditions. The constant conditions chosen here are similar to those that appeared as constant or varied in two previous experiments: the CAORF and the Channel Width experiments. This similarity maximizes comparability between experiments. The selected conditions are summarized in Table 3.

1. The Channel Dimensions. The scenario contains two channel segments, 2 and 2-1/2 nm long, connected by a turn, as illustrated in Figures 2 and 3. The channels are 500 feet wide. The 500-foot wide channel was chosen after the Channel Width experiment demonstrated that this width, rather than the wider width to which it was compared, requires greater understanding of channel marking. (Note that the depth of the channel was adjusted to the size of the ship. One foot of clearance under each ship was necessary to obtain the planned maneuverability. Figure 1 lists the channel depth for each scenario.)

2. The Turn Characteristics. The turns in this experiment are 35-degree noncutoff turns. In the CAORF experiment, the 35-degree noncutoff turns were the most difficult. For these, performances showed a high degree of sensitivity to differences in marking. The dimensions of the turn with the one or three buoys is illustrated in Figure 4. The relationship of the turnmarking to the straight channel marking is illustrated in Figures 2 and 3.

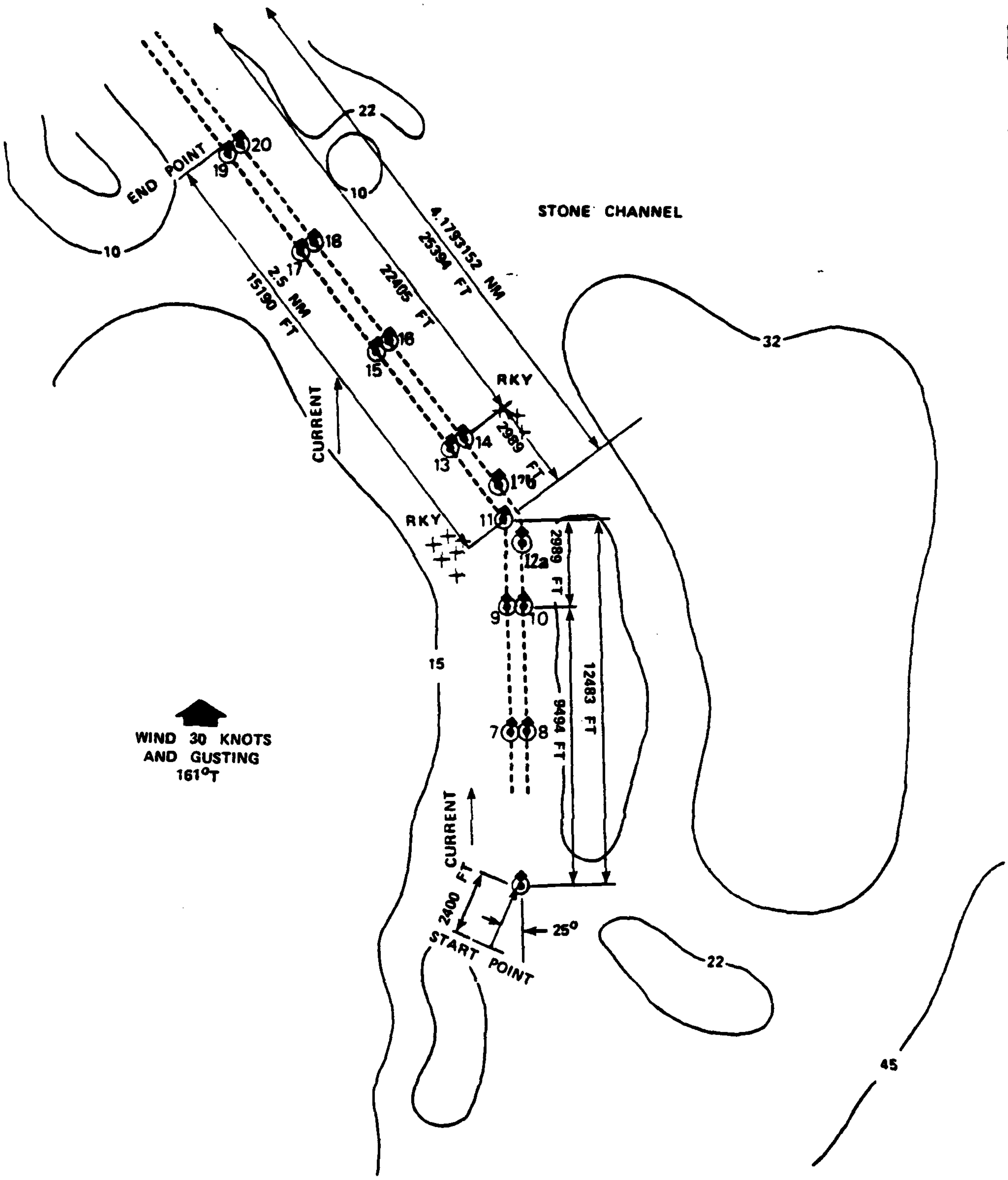


Figure 2. Chart 1 - High Information Density

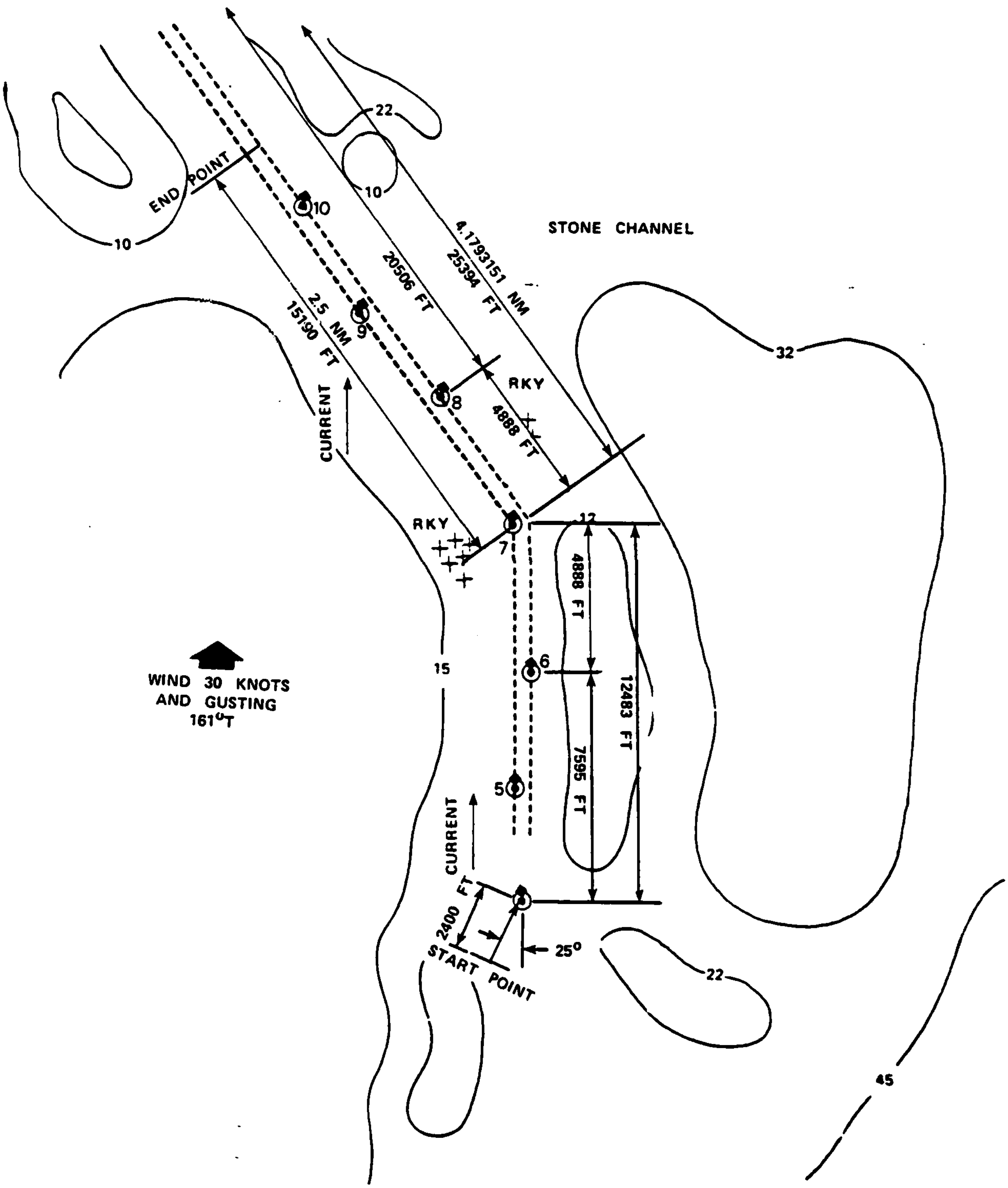


Figure 3. Chart 2 - Low Information Density

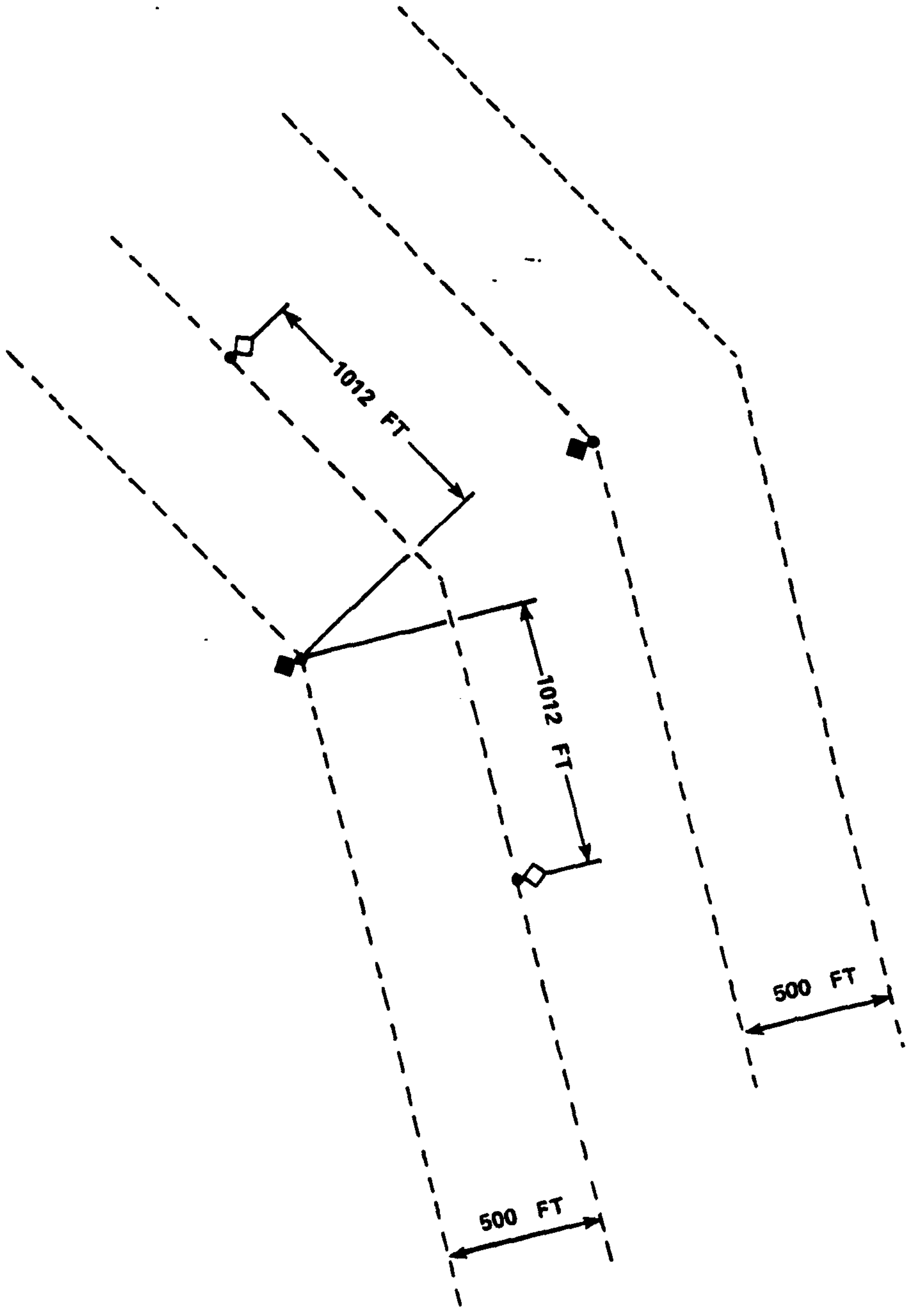


Figure 4. The Turn Conditions

TABLE 3. THE CONSTANT CONDITIONS

1. Channel Dimensions:
   - 2, 2-1/2 nm length
   - 500-foot width
   - Shallow depth
2. Turn Characteristics:
   - 35-degree noncutoff turn
3. Environmental Conditions:
   - Daytime, 1-1/2 nm visibility
   - Wind and current vary over scenario
4. Bridge Conditions:
   - Helmsman
   - Engine order telegraph
   - Gyrocompass
   - Chart
5. Visual Scene:
   - Ship's bow
   - Sea, sky demarcation at 1-1/2 nm
   - Red, black buoys at 1-1/2 nm
6. Performance Requirements:
   - Enter channel with crosscurrent
   - Move to centerline with following current
   - Align ship to turn
   - Make turn
   - Stabilize ship after turn with decreasing crosscurrent
   - Maintain channel centerline with decreasing crosscurrent

3. Environmental Conditions. The daytime and 1-1/2 nm visibility conditions that successfully revealed differences in aids to navigation conditions in the Channel Width experiment were retained. The current and wind follow patterns similar to that used in the Channel Width experiment. The wind is following in the first leg and broad on the port quarter after the turn, with some variation in direction. The wind speed is 30 knots, again with some variation. The current, too, is following in the first leg and broad on the port quarter after the turn. It decreases in velocity from 1-1/4 knots at the beginning of the scenario, to 3/4 knots after the turn, to zero at the end of the run. The wind and current are described in greater detail in Appendix C. The consequences for performance of these effects are discussed in Section 3.

4. The Bridge Conditions. The pilot has available the following:

- A helmsman to receive his orders.
- A gyrocompass.
- An engine order telegraph (with the opportunity occasionally taken to increase his speed in the turn).
- Charts of the channel with the course and buoy locations.
- A diagram of the current conditions.
- No radar. (This is an experiment in visual piloting.)

5. The Visual Scene. A sample visual scene provided for guidance during the scenario is illustrated in Figure 5. The small bow image for the 30,000 dwt tanker with a midship bridge, a 45-foot height of eye appears ahead on the center screen with a tall jackstaff that intersects the demarcation between the sea and sky. The illustrated ship has a drift angle to compensate for the current in Leg 2. The daytime, 1-1/2 nm detection range condition is represented by a gray sea and blue sky. The 17-foot unlighted buoys first appear at the 1-1/2 nm demarcation as black, vertical lines. As the ship moves closer to them, they increase in height, width, and detail. The right-hand buoys are more obviously dark red as they come closer. As the buoys pass abeam, it is possible to compare their height to the bottom of the bridge windows on each side. Images of the bridge wings block out the buoys just before they pass abeam. (Note that the bow image and the bridge wings varied as described in Section 1.2.)

6. The Performance Requirements. The piloting tasks the pilot is instructed to perform are illustrated in Figure 6. The ship is initialized at a point 2400 feet outside the channel with a heading of 008°T. The pilot is instructed to enter the channel to the left of a sea buoy at the center of the channel. The current is running at 1-1/2 knots parallel to the channel he is about to enter, so it is broad on the starboard quarter as he begins the entry into the channel. (This entry into the channel is meant as a familiarization with the specific ship and speed. There was a separate familiarization run for the turn, wind, and current.) Once in the channel, the pilot is instructed to take the ship to the centerline. He may leave that centerline when ready to negotiate the turn by his own strategy. As he enters the new leg, the wind and current are broad on his port quarter. He is asked to return to the centerline in the next leg as soon as possible. Given the current velocity of 3/4 knots and his speed through the water of 6 knots, he needs a drift angle of 4 degrees to maintain the course of the channel. As he attempts to return to the centerline, the current velocity and the necessary drift angle decrease, reaching zero at the end of the scenario. The wind maintains the same average intensity throughout the run, varying somewhat in direction. The runs lasted 45 minutes or less. The instructions to the pilot appear as Appendix C.

1.4 DATA COLLECTION AND ANALYSIS

1.4.1 DATA COLLECTION.

A variety of performance measures will be collected for use in evaluating the scenario conditions. They include the following measures:

1. The principal measure is the ship's crosstrack position as a function of alongtrack position. (The graph of this relationship is referred to as a track plot.) A variety of related dependent variables are also recorded. When the ship crosses the data lines diagrammed in Figure 7, or when the pilot makes the responses described below, the computer records the following measures:

- Time of event.
- Ship's center of gravity position.
- Ship's bridge position.
- Ship's velocity relative to the ground.
- Ship's true heading.
- Rate of turn.
- Rudder angle.

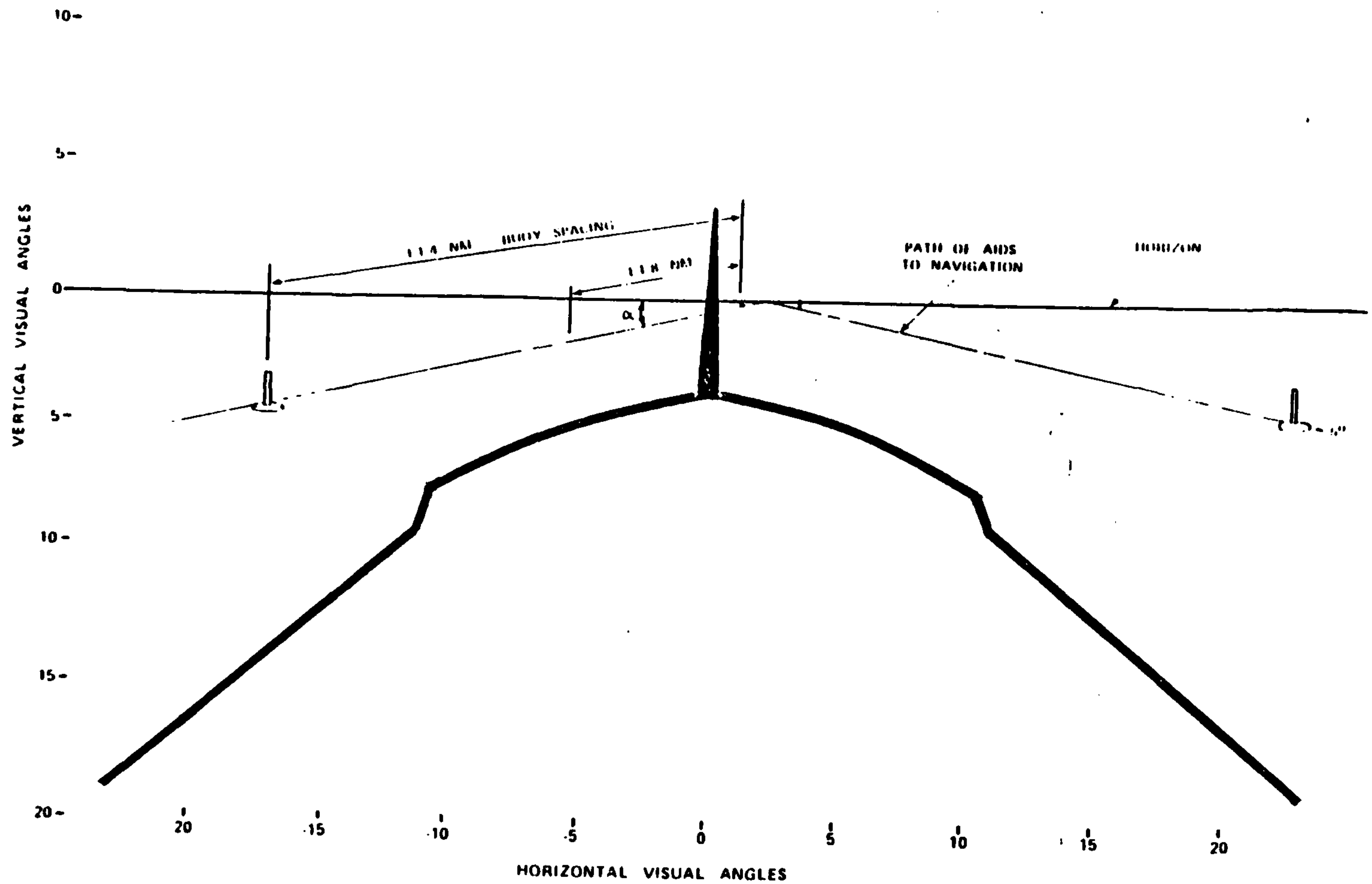


Figure 5. The Visual Scene

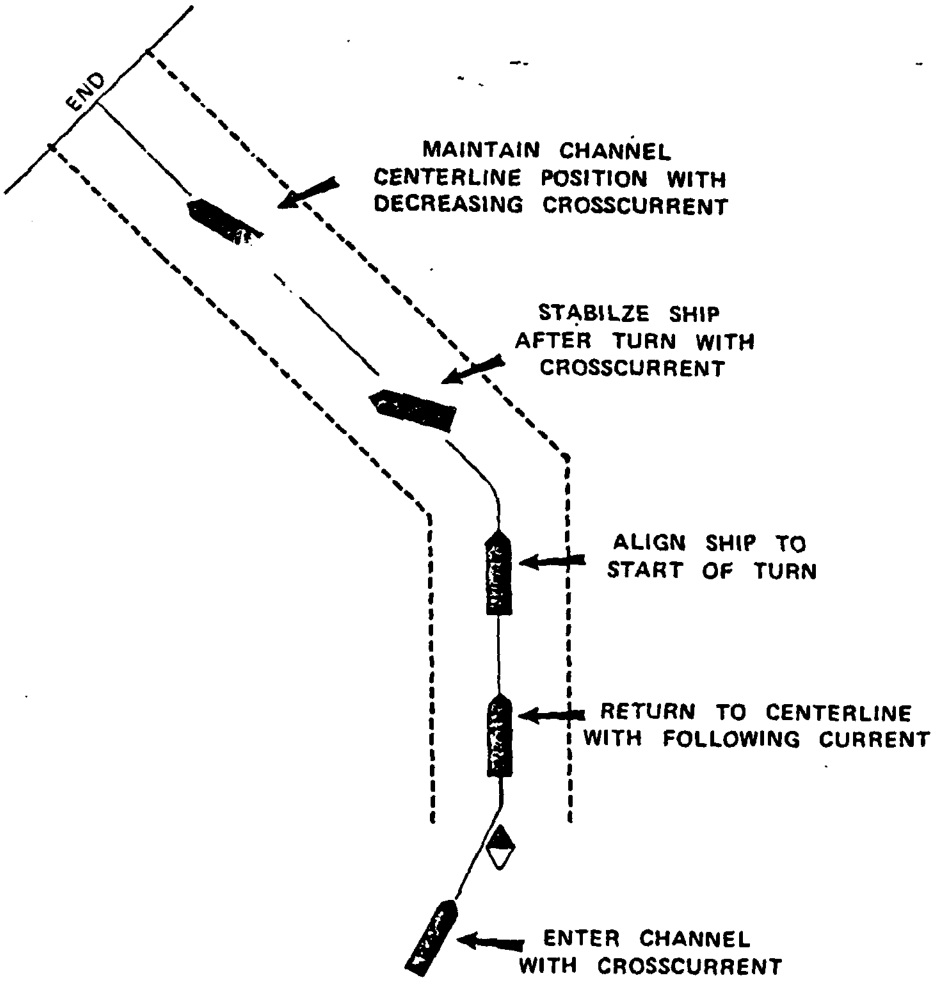


Figure 6. The Performance Requirements

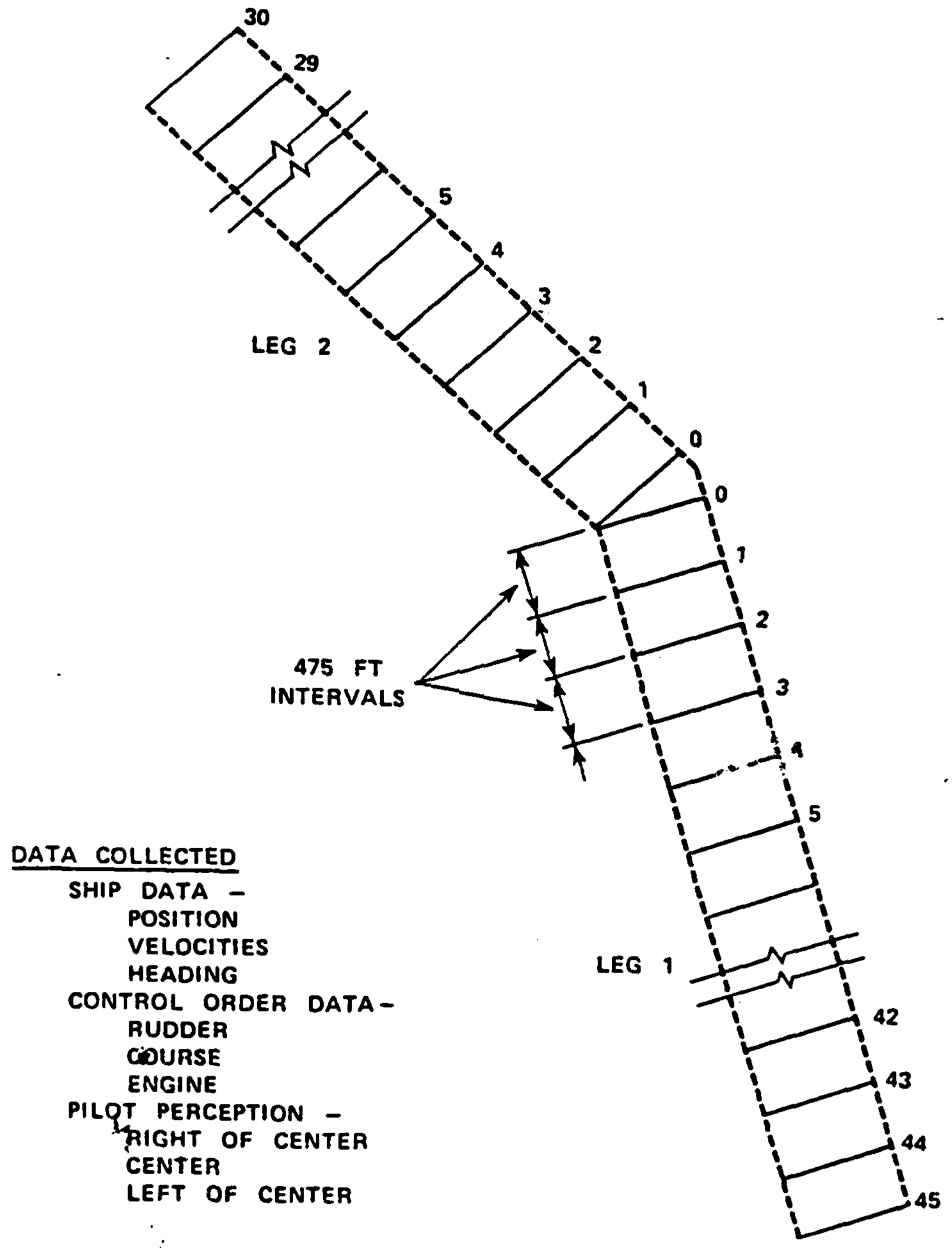


Figure 7. Data Collection Lines

- Course made good.
- RPM of propeller.

2. The subject's course, rudder and engine orders are recorded with alongtrack position and a variety of other dependent measures.

3. A direct measure of the subject's perceptions of his position in the channel is taken. A response panel is used which (along with a support program) enables the subject to report his estimate of his crosstrack position as a function of his alongtrack position. For scenarios with adequate buoy placement his perceptions should be more accurate.

4. A postsimulation questionnaire allows the subject to comment subjectively on the conditions of each scenario and his strategies. This quesionnaire appeared in the presimulation report cited earlier and formed the basis for the preliminary observations.[9]

1.4.2 DESCRIPTIVE ANALYSIS OF THE DATA. The principal descriptive analysis is a compilation of data on the position of the ship's center of gravity. The basic measure of the ship's crosstrack position will be treated as illustrated in Figure 8. The mean and standard deviation are calculated at each data line for the set of conditions to be described. The first set of axes shows the means; the second, the standard deviation. On the last axes is a "combined plot" which shows the band formed by the mean and two standard deviations to either side of it against the boundaries of the channel. The band encloses 95 percent of expected transits under the experimental conditions sampled. The placement (mean) and width (standard deviation) of this band within the boundaries of the channel are together a quantitative description of the set of transits under these conditions, and, therefore, of the performance of the buoy arrangements.

The trackkeeping portions of the scenario are the easiest to interpret. It is assumed that, because of instructions, the pilots are attempting to keep the ship on the designated track. The distance of the mean off the centerline and the spread measured by the standard deviations are indications of the performance of the buoy arrangement for the conditions sampled. Therefore, the best buoy arrangement is one that puts the mean of the distribution on the trackline and minimizes the standard deviation. Performance in the maneuvering portions is more difficult to interpret. The distribution of crosstrack portions contains the variations in pilots' strategies as well as the performance of the buoys in guiding them in those strategies. An adequate buoy arrangement should keep the combined plot well inside the channel.

There is an assumption in this discussion that the precision in piloting performance that a buoy arrangement affords is related to the safety of that channel: a safely-marked channel is one that results in a distribution of transits that is well within the channel boundary for both trackkeeping and maneuvering. It should be reemphasized that these measures are derived from an experiment and not a real-world situation. They are measures of performance under the experimental conditions (the experimental design and the simulation) used. For application to

[9] Eclectech Associates. "Preliminary Observations of the Ship Variables Experiment." Technical Memorandum, February 1981.

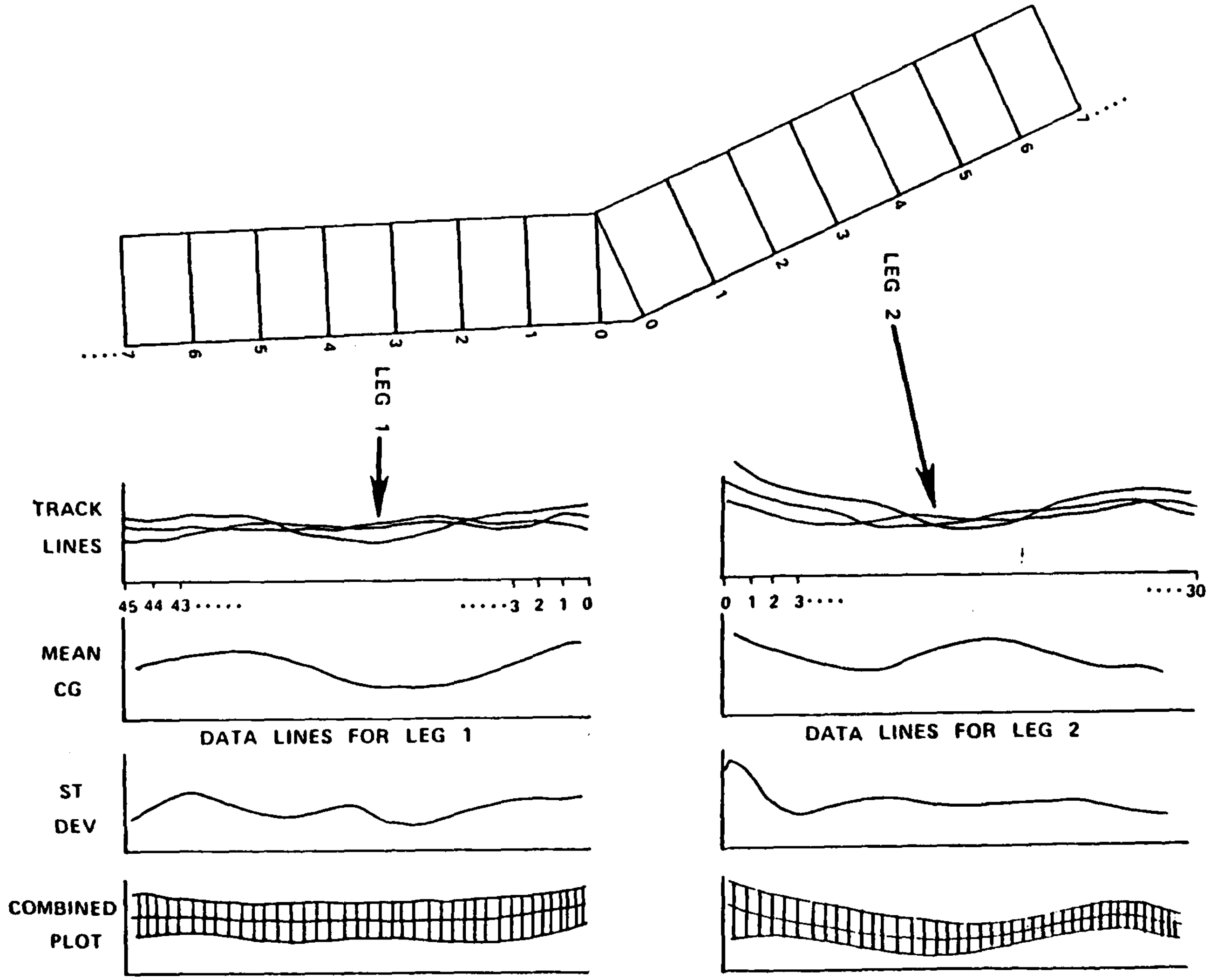


Figure 8. Descriptive Analysis of Ship's Center of Gravity Data

real-world channels, they must be considered relative measures of the performance of buoy arrangements or channel conditions. The interpretation of these performance measures as probability of grounding, for example, would be incorrect pending validation of such interpretation in the real world.

1.4.3 THE INFERENTIAL TESTS. The experiment can not be analyzed with any single inferential procedure for the following reasons.

1. Each comparison is logically a separate experiment.

2. To adequately describe the data (the crosstrack position of the ship's center of gravity) requires both the mean and the standard deviation (or variance), and these must be calculated at each data line over the scenario.

Instead, for each separate comparison the mean and standard deviations for each component scenario will be selected at critical data lines and tested for the significance of their differences by the following procedures which are described in McNemar.[10]

The Means:

- When means from two conditions are to be compared, a t-test will be used.

- Given the inherent asymmetry of performance in some of the conditions, it is of interest to evaluate the amount of displacement of a single mean from the centerline, the supposed intended track. For this purpose a t-test for a single mean which compares a single mean to a hypothetical mean will be used.

The Standard Deviations:

- The standard deviations of the conditions will be compared in pairs dictated by the logic of the comparisons. They will be compared as variances, using variance ratios, or an F-test.

[10] Quinn McNemar. Pyschological Statistics, Fourth Edition. John Wiley and Sons, Inc., New York, 1969.

Section 2

THE EFFECT OF BOW IMAGE FOR THE 30,000 DWT TANKER

2.1 OVERVIEW

Two different bow images were run with the hydrodynamics of the 30,000 dwt tanker: a larger bow like that used in the CAORF experiment and a smaller bow like that used in the Channel Width experiment. It was found that differences in bow images result in a difference in performance when there is a following current with the advantage to the larger bow. The interpretation is suggested that the larger bow is advantageous in making relative judgments of distances to the indicated channel edges when the following current allows a symmetrical view of those edges. These data mean that superior CAORF performances with a crosscurrent cannot be the result of CAORF's larger bow image. The data also suggest that the ship's visual characteristics contribute to piloting in the real world.

2.2 THE EFFECT

This comparison can be interpreted in two different ways. First, it is a comparison between two simulations. The several visual experiments in the project are meant to provide a pool of findings too large to be the result of one experiment. To allow this pooling, it is necessary to provide transitions between experiments done on different simulators, or with differently simulated conditions. This comparison provides such a transition between the conditions of the CAORF experiment and of the Channel Width experiment. Such a comparison was proposed in a discussion in the Channel Width Principal Findings Report, Section 3. This comparison can also be viewed as the evaluation of a ship variable: *Does the visual configurations of the ship itself have an effect on piloting with visual aids?*

Scenarios 1 and 2 differ in the visual configuration of ownship. (The dynamics were of the same 30,000 dwt tanker.) Scenario 1 presented the bow image used in the Channel Width experiment and illustrated in Figure 9. It has a smaller or lower bow than the others in this experiment, filling less of the front screen and leaving more visual space between its edge and the buoys. It had no bridge wings. Scenario 2 presented a larger bow, a tracing of the one used for the CAORF experiment. It is illustrated in Figure 10. On the side screens, it presented a view of the bridge wings as illustrated in Figure 11. The bridge wings were added to the "CAORF" bow conditions because of differences in the dimensions of the CAORF and USCG/EA bridges described in the Channel Width report. Standing at the viewing point at the center of the larger CAORF bridge, the pilot cannot see the buoys pass abeam because of the physical structure of the bridge. Standing at the viewing point at the center of the USCG/EA bridge, he can see them pass abeam, if no bridge wings are provided. The simulated bridge wings make the two simulations more comparable.

It was expected that the advantage, if there was one, would be to the larger bow. The two bow images are superimposed in Figure 12 which is repeated from the Channel Width report. The bows are shown with the 3-degree drift angle required by the crosscurrent in Leg 2. The larger bow enhances the information the pilot can get from the buoys in a number of ways. In maneuvering or turning, the movement of the larger bow relative to the visible buoys is a better cue for the perception of

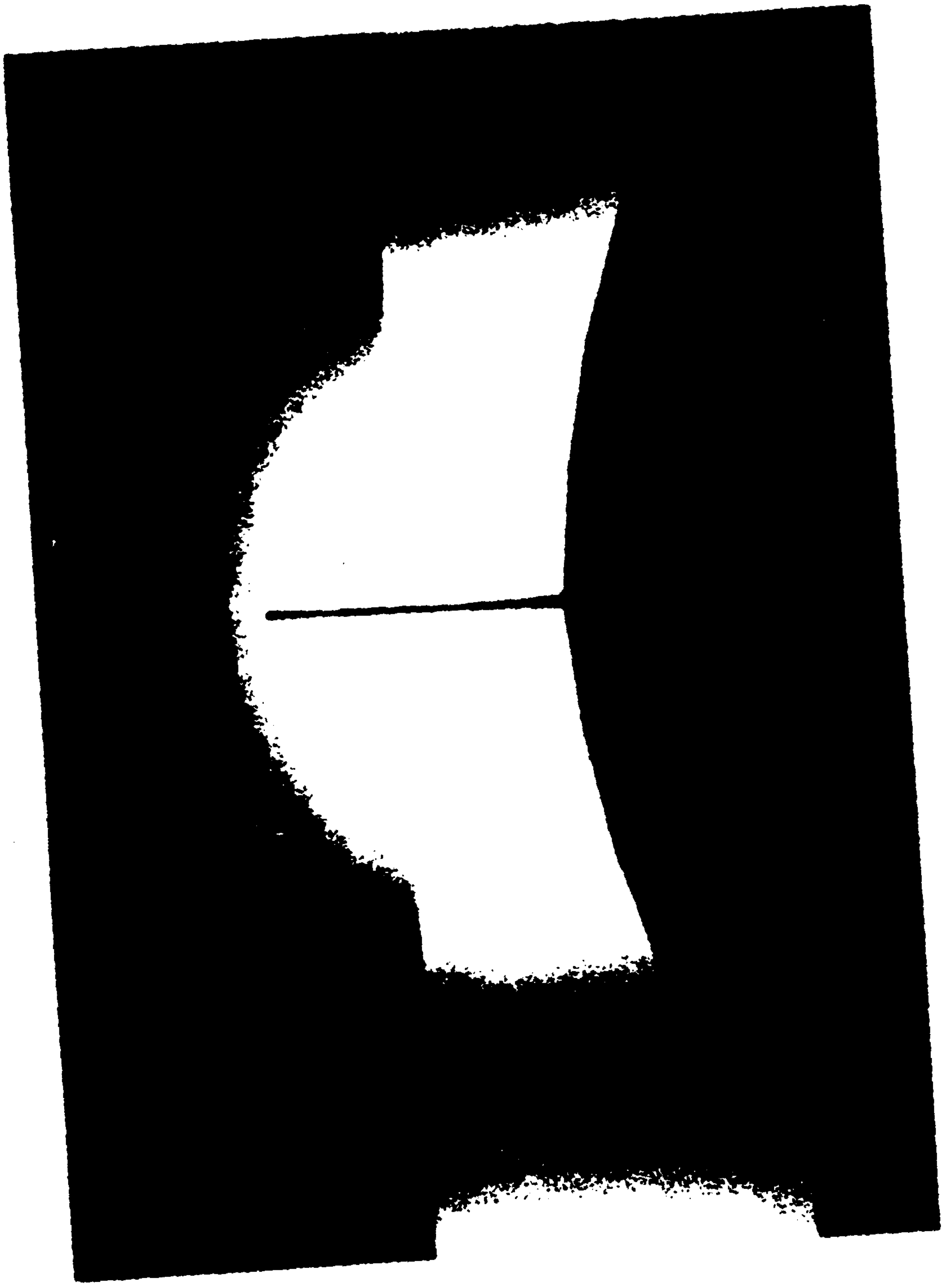


Figure 9. Bow Image for Scenario 1

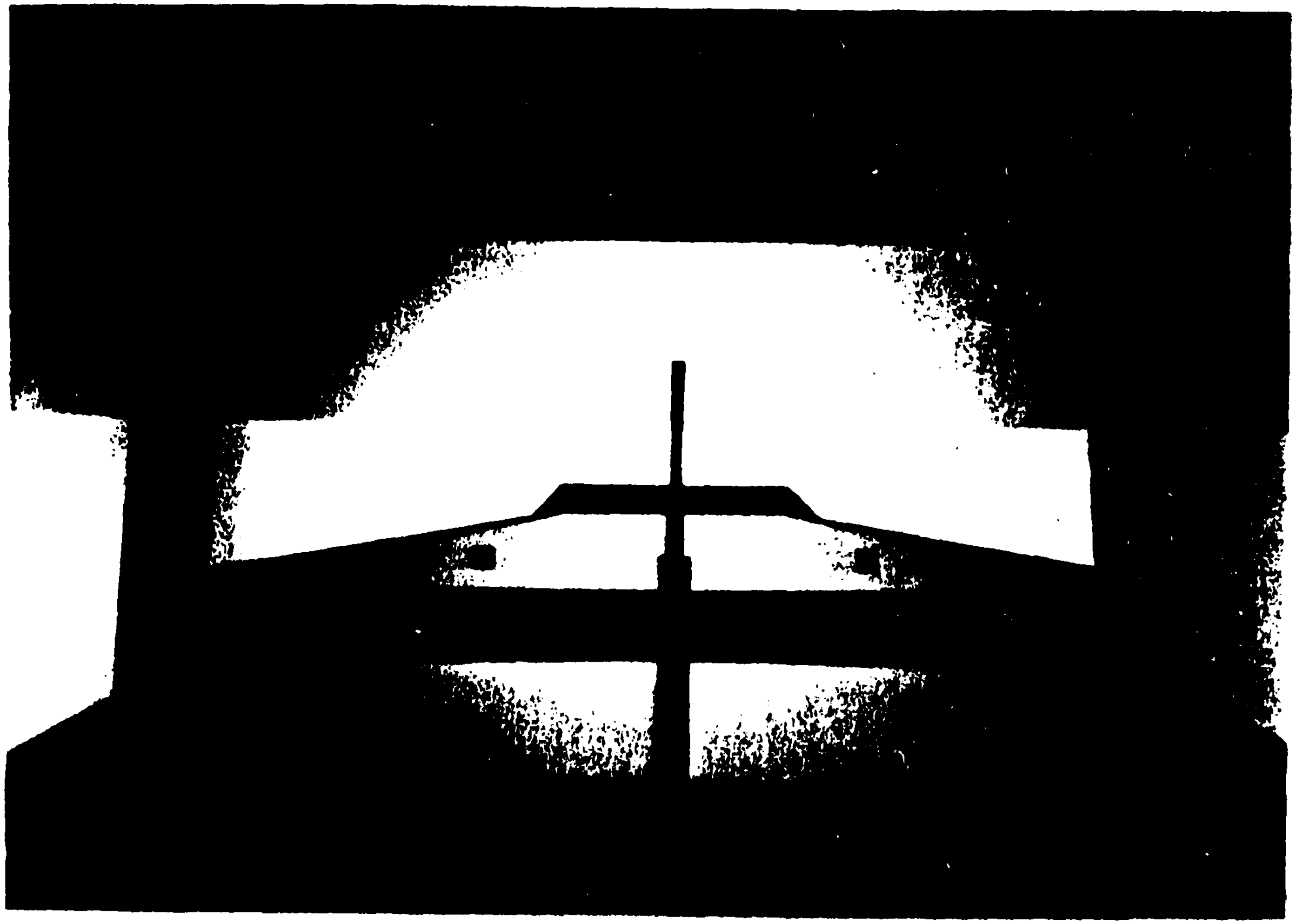


Figure 10. The Bow Image for Scenario 2.

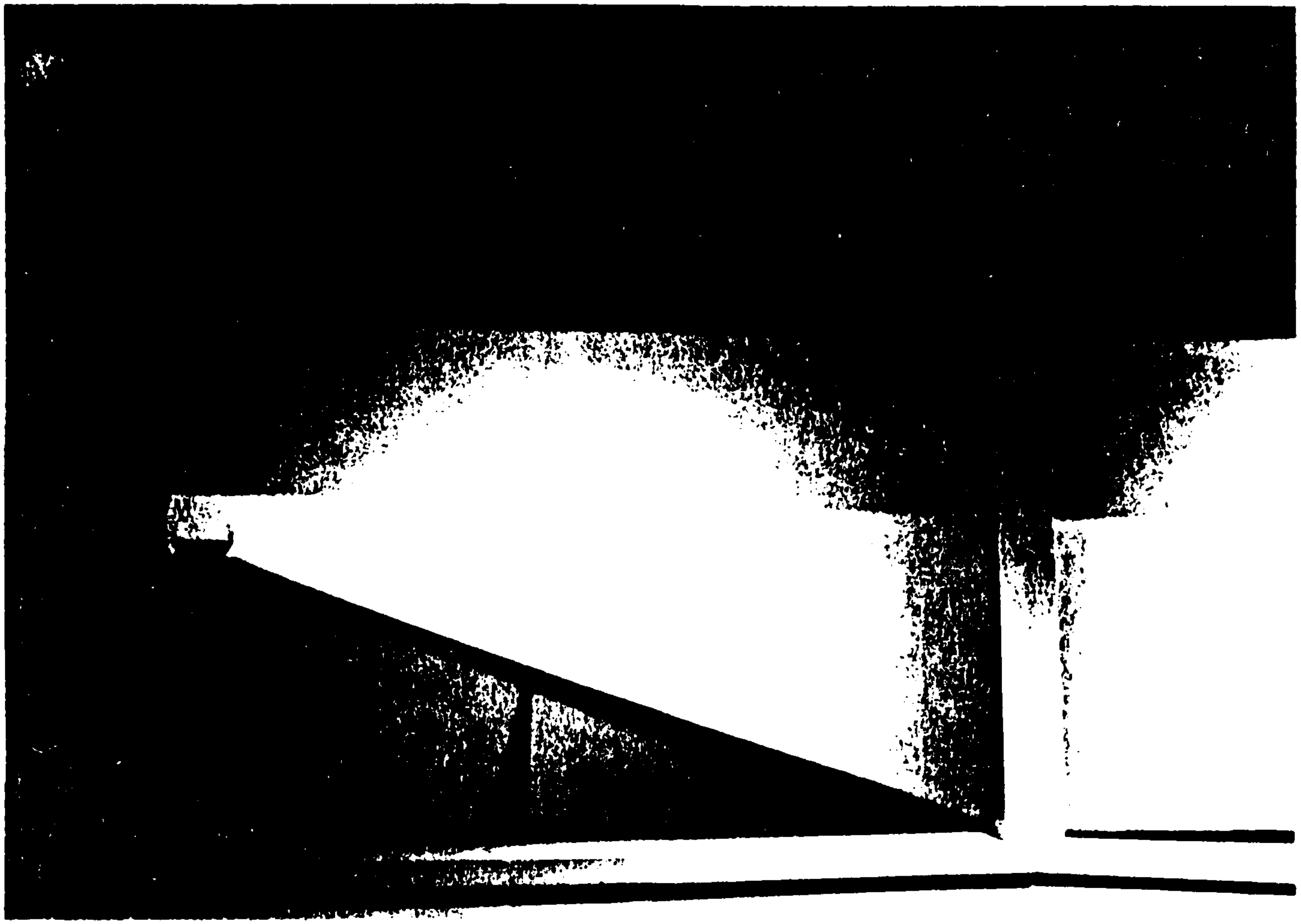


Figure 11. The Bridge Wings for Scenario 2

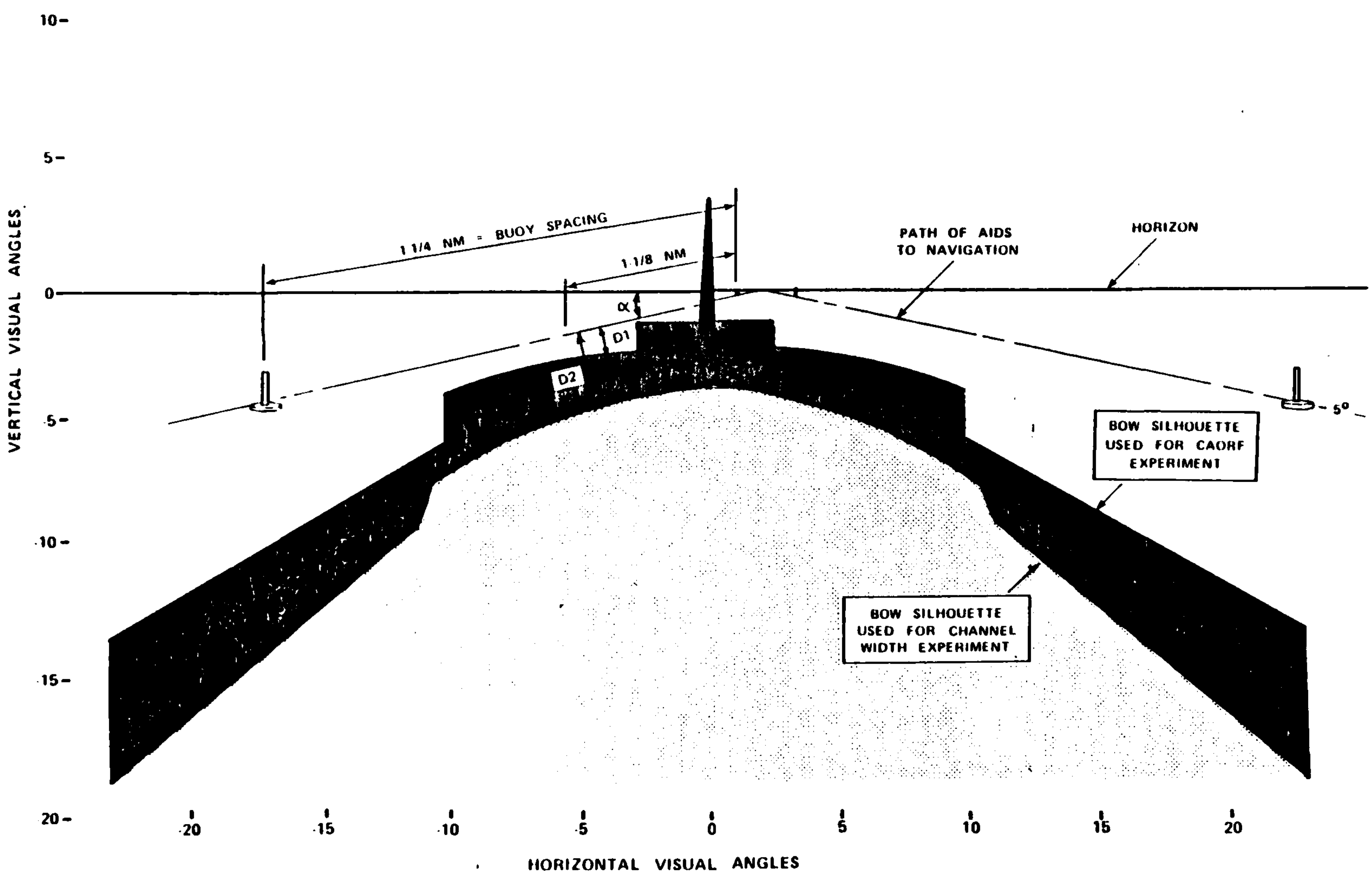


Figure 12. The Silhouettes of the Bow Images

rate of turn. In trackkeeping the larger bow is visually closer to the buoys, or to the channel edge, allowing the pilot to make easier comparisons of shorter distances: that is, D_1 versus D_2 in Figure 12. Also, in trackkeeping the larger more complex bow provides a greater variety of reference points against which the movement of the buoys to each side can be matched. The more complex silhouette of the large bow is apparent in Figure 12.

Performance differences between the two conditions occurred in Leg 1. The distributions of transits for the two conditions are compared in Figure 13. (See section 1.4.2 for an explanation of the derivation of this type of plot.) In each plot the peak at Data Line 30 is the initialization point for the scenario. The distribution widens as the ships approach and pass the sea buoy. The upper corner of the sea buoy represents its position on the centerline of the channel. Some runs in both conditions overshoot the centerline. (This condition has long-spaced, staggered buoys.) The distribution narrows as the pilots have time to find and maintain the centerline. There is some increase in the width of the distribution as the pilots prepare to enter the turn. The width of this band is greater for Scenario 1 with the smaller bow image; performance is more precise in Scenario 2 with the larger bow image. The widest distribution for both conditions is at Data Line 23. Here, the standard derivation for the smaller bow is 114 feet, while for the larger bow, it is only 81 feet. At this point these values are not significantly different. However, for most of the leg the differences between the standard deviations in the two conditions are significant at the 0.10 level. (A difference that large would have occurred by chance 10 percent of the time.) The means are not significantly different. Neither the standard deviations nor the means in Leg 2 are different. Performance with the larger bow is superior when there is a following current.

Apparently, the larger bow image did enhance the information to be had from the available buoys, at least in Leg 1 with a following current. Figures 14A and B show the helm orders in Leg 1 for the two conditions. The larger bow condition in Figure 14B shows more rudder orders and more total orders. A greater number of rudder orders and total orders was associated in the Channel Width experiment with greater buoy density – more information. The difference in helm orders supports the interpretation that the larger bow enhances the information value of the buoys.

Possible mechanisms for enhancement were suggested above. The data showed that the enhancement effect did not continue into Leg 2 with the crosscurrent and the required drift angle. Whatever use the pilot made of the large bow in estimating position required a symmetrical orientation to the buoys to have its effect. Therefore, the possible mechanisms should be reworded to reflect this symmetry. Possibly, the pilot made <u>relative judgments</u> of the distances <u>on each side</u> of the bow to the buoys, or the estimated edge of the channel, and made them more accurately when the distances involved were smaller. Or possibly, he used the more distinctive discontinuities in the larger bow to compare the movement of the buoys as they passed <u>to either side</u>. Possibly, he did both. That the advantage to the larger bow is in Leg 1 (with a following current) but not in Leg 2 (with a crosscurrent), has implications for the explanation offered in the Channel Width report for the superiority of performance at CAORF. It was suggested that the pilot used the bow to estimate the distance to a single buoy as it passed close and abeam, with an advantage to the larger CAORF bow. Apparently, this is not the case. That the larger bow did not enhance performance in Leg 2 where the CAORF performance showed an advantage, obviates the bow as the critical difference between the two simulations. Other possible causes for the difference are discussed in Section 3 of the present report.

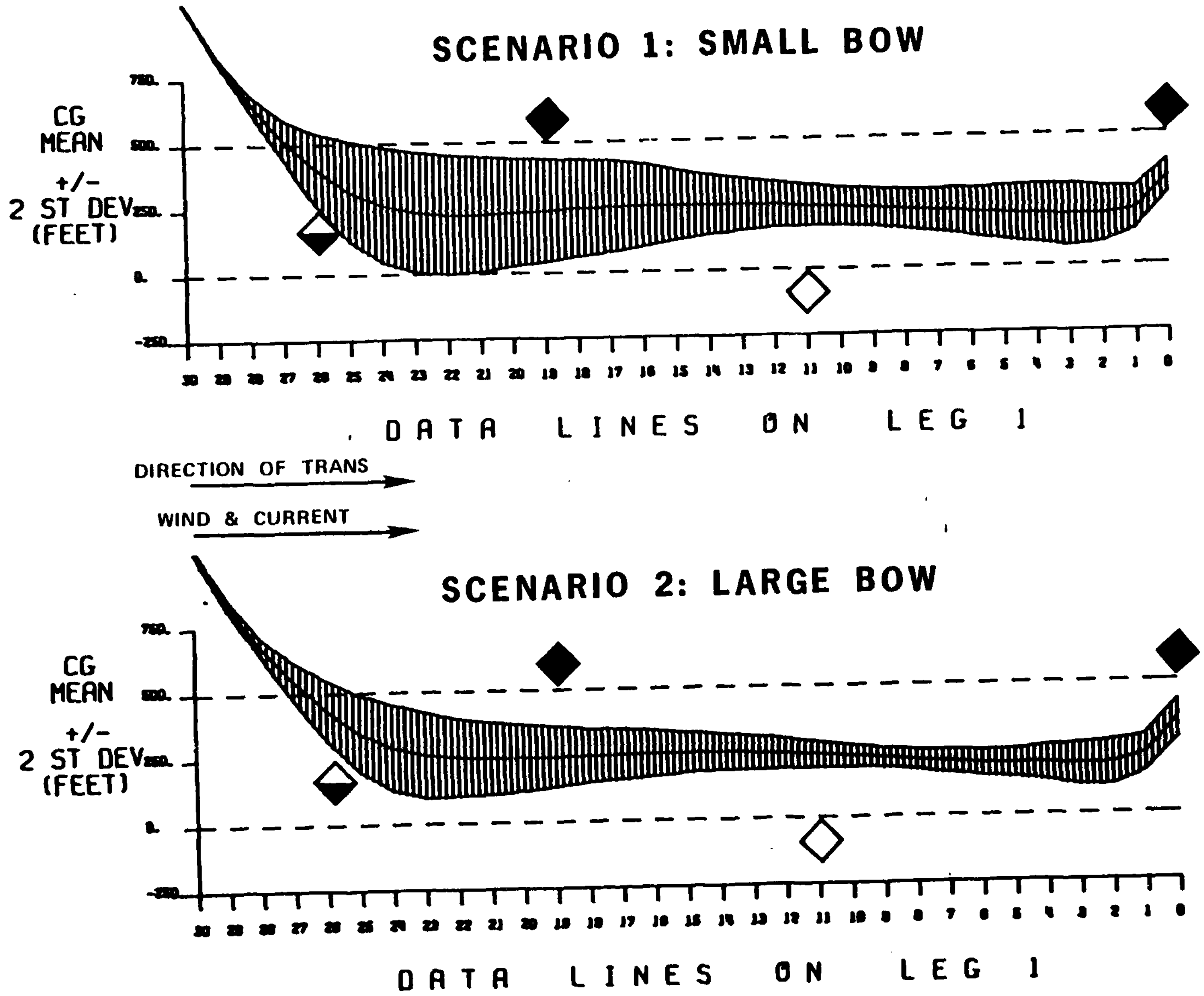


Figure 13. Performance in Leg 1 with the Two Bow Images

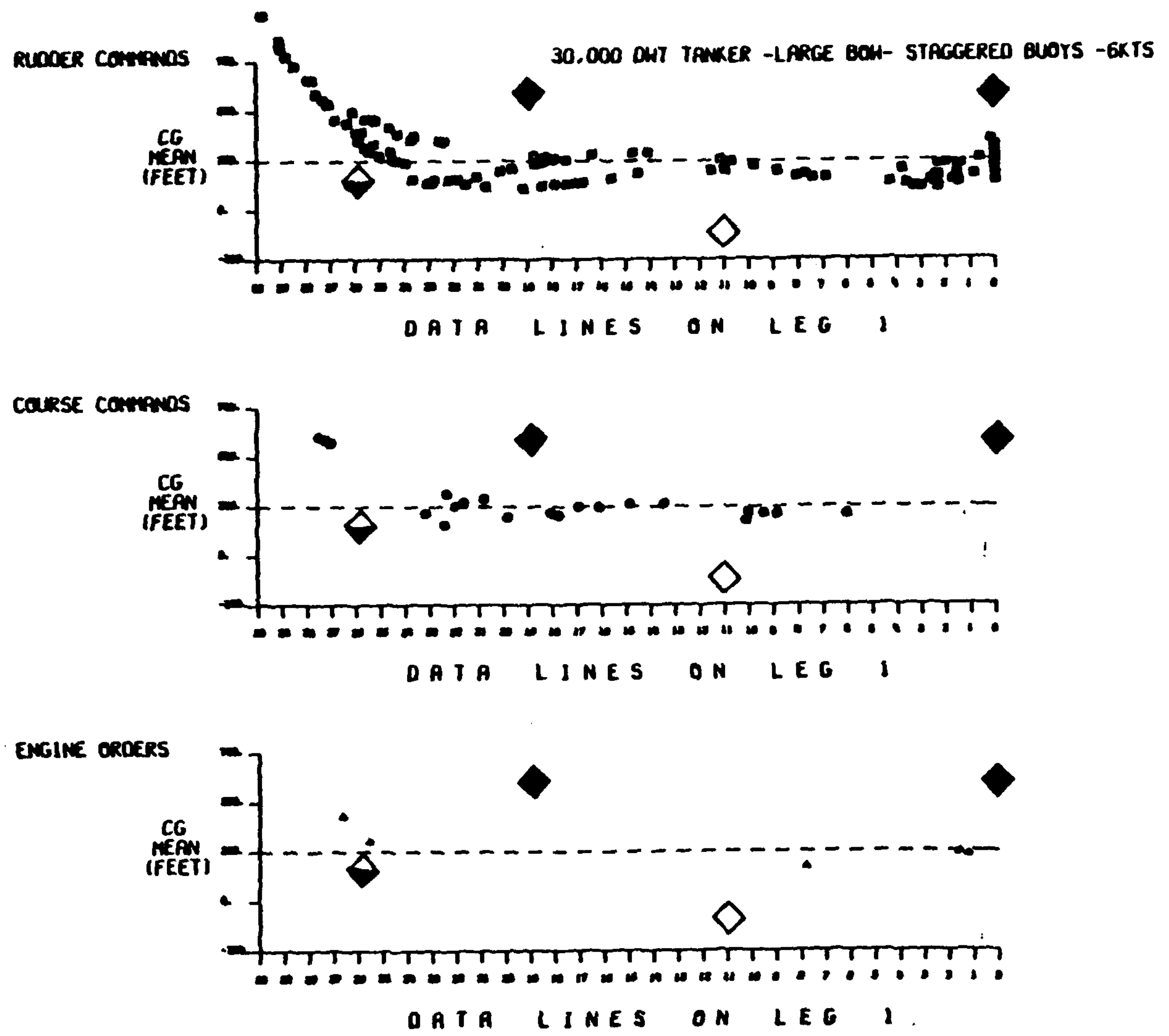


Figure 14a. Helm Orders in Leg 1 for Large Bow Image Condition

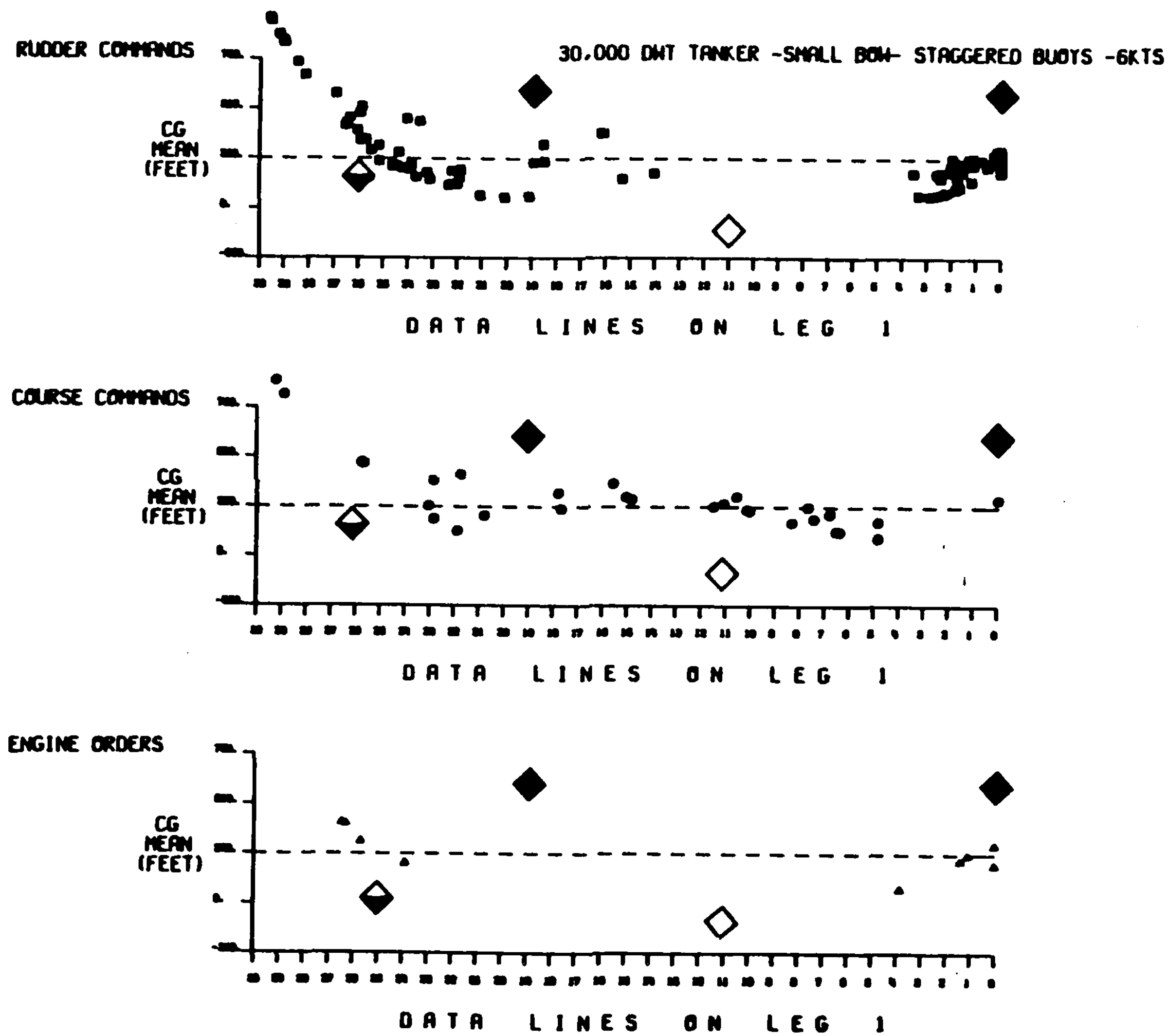


Figure 14b. Helm Orders in Leg 1 for Small Bow Image Condition

The results of this comparison can be interpreted as a shiphandling effect as well as a simulation effect. In post-simulation discussion, the pilots agreed that in both the simulator and the real world, they used "whatever is available". To varying extents for individual pilots that includes the bow ahead, the window mullions, and the bridge wings. This use of the ship's visual configuration is not something that can be planned in the design of an aid to navigation system. It is the pilot's responsibility to accommodate to the visual characteristics of the ship as he accommodates to its dynamic characteristics.

Section 3

A REEVALUATION OF SIMULATOR DIFFERENCES

3.1 OVERVIEW

The evaluation of the Channel Width experimental data suggested changes to the USCG/EA simulation to more closely approximate that at CAORF. With greater similarity to CAORF in simulation than was the case for the Channel Width experiment, the results of the USCG/EA simulation were found to more closely approximate the CAORF results. With what appears to be a meaningful selection of representative data points, *the two simulators resulted in statistically identical absolute values for the two conditions and in almost statistically identical differences between high and low information density conditions.*

3.2 THE REEVALUATION

It was pointed out in Section 2 that the intention to pool findings from several experiments makes it necessary to constantly evaluate similarities and differences among them, both in the simulation and in the resulting performance. A comparison between the CAORF findings and the Channel Width findings obtained on the USCG/EA simulator was included in the report of the latter experiment. There it was reported that the absolute magnitudes of representative standard deviations were larger for the USCG/EA simulator, demonstrating poorer overall performance. However, differences among the various conditions simulated were similar to those reported to CAORF. It is these differences that are of major importance for the aid to navigation project. The evaluation of these differences was possible with both the CAORF and teh earlier USCG/EA Channel Width simulation.

A number of possible reasons for the discrepancy in observed values were suggested in the Channel Width report. One of these, a difference in bow images, was eliminated in Section 2 above. Another possibility suggested was a difference in wind effects. Figure 15 compares the wind direction function for the three experiments. It was shortly after the turn that the Channel Width performance showed an increase in crosstrack standard deviation that did not occur at CAORF. As can be seen in Figure 15, this increase corresponds to a greater change in wind direction for the Channel Width simulation, approximately 13 degrees. The third function in the figure is for the present, Ship Variables, experiment. The wind direction condition now more closely matches that for the CAORF experiment. The ship variables data compared here with the CAORF data were collected with this more similar wind condition. The wind and current effects are further described in Appendix C.

Two of the scenarios in the present experiment are comparable to conditions that appeared in the CAORF experiment. These are Scenarios 2 and 5 as summarized in Figure 1. Scenario 2 has the straight channel segments marked with staggered buoys spaced at 1-1/4 nm; Scenario 5 has gates spaced at 5/8 nm. The ship used in both these scenarios was the 30,000 dwt tanker with the large bow image run at 6 knots. The CAORF experiment used the same ship, bow image and speed. The comparable data from that experin .nt comes from two pools of four scenarios each, scenarios that differed in turn conditions. For this reason, the turn conditions are not comparable and this discussion will not include turn performance. These CAORF data are the same that were used in the Channel Width comparison.

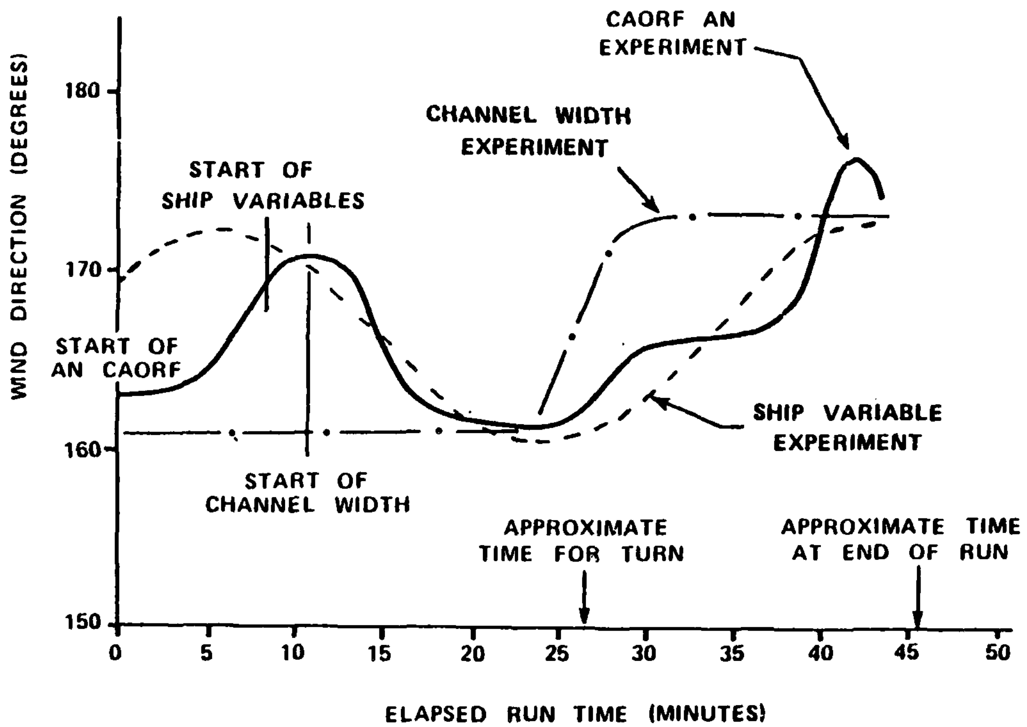


Figure 15. Wind Direction Functions For the Three Experiments

The conditions in Scenario 5, and the comparable CAORF scenarios, had a high density of buoys, or visual information: gated buoys spaced at 5/8 nm as illustrated in Figure 2. With a visibility of 1-1/2 nm, the conditions allow a view of two gates at all times. Representative performance data selected for this discussion is presented in Figure 16. Leg 2 performance is used because there were little differences among conditions in Leg 1. The standard deviations are used because they showed greater sensitivity to the conditions involved here. The differences between the means corresponding to these standard deviations were trivial and not statistically significant. The plot shows the crosstrack standard deviation for each successive data line for the length of Leg 2 for both experiments. The buoys indicated on the plot are meant to show the alongtrack position of the buoys in the scenario. Their vertical placement on this plot is meaningless. The turn pullouts at the beginning of the plots are not comparable because the CAORF data is pooled over a variety of turn conditions. It is necessary to select a point somewhere beyond the turn to represent the straight channel segment. Notice that the two functions come together at each gate. The first gate after complete recovery from the turn is at data line 15, or 1.17 nm beyond the turn. At the point the standard deviation for CAORF is 43 feet; while for the USCG/EA data, it is 36 feet. These values are not significantly different statistically. These data imply that given a gate up uphead, with the high degree of certainty of a short term destination that given a gate presents the two groups had the same degree of success in achieving that destination. A second comparison can be made at the end of the scenario. As the crosscurrent decreases, the standard deviation for both groups approaches the same steady state value. At the end of the run at data line 30, or 2.34 nm beyond the turn, the CAORF standard deviation is 36 feet while the USCG/EA value is 33 feet. A test of this difference is not necessary. They are the same.

A similar comparison can be made for low buoy, or information, density conditions. Scenario 2 with staggered buoys spaced at 1-1/4 nm is illustrated in Figure 3. With a visibility of 1-1/2 nm the pilots saw at least two buoys ahead at all times, one on each side, but never two on each side outlining both channel edges ahead. The crosstrack standard deviations for Leg 2 for the two conditons are compared in Figure 17. Here, the buoys on the plot indicate the alongtrack position and the side of the buoys in the scenario. Again, the turns at CAORF are pooled and not comparable. The choice of a representative point is not as obvious for the staggered is 61 feet for CAORF and 58 feet for USCG/EA. This difference is not statistically significant. (The means are not significantly different at this point, either.) As was the case for the gated conditions, when the two groups had the same certainty about a goal, they had the same degree of success in achieving that goal. At the end of the scenario, the steady state value is 43 feet for CAORF, and 53 feet for USCG/EA. These are not significantly different.

The comparison between the two simulations can be made in terms of the absolute values obtained for given conditions or in terms of the differences between values obtained for several conditions. The simulation by information density interaction is presented in Figure 18 to allow both types of comparison. The values here are the standard deviations in Leg 2 at data line 15, the point of maximum certainty about a short term goal. The absolute values for the low information density condition are 61 and 58 feet; for the high information density condition, they are 43 and 36 feet. Each pair is not significantly different at even the 0.10 level and

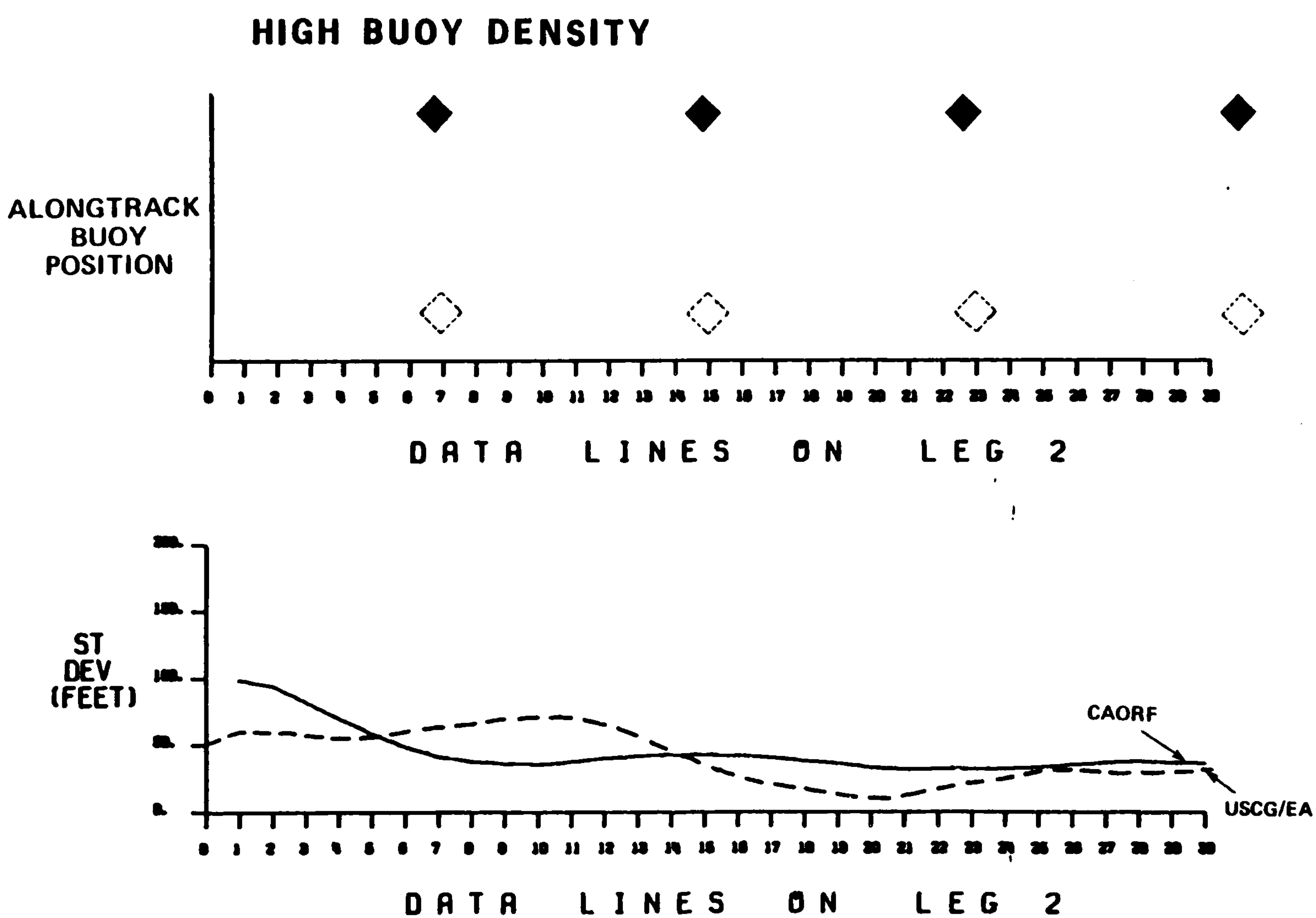


Figure 16. Performance in the High Information Density Condition for the Two Simulations

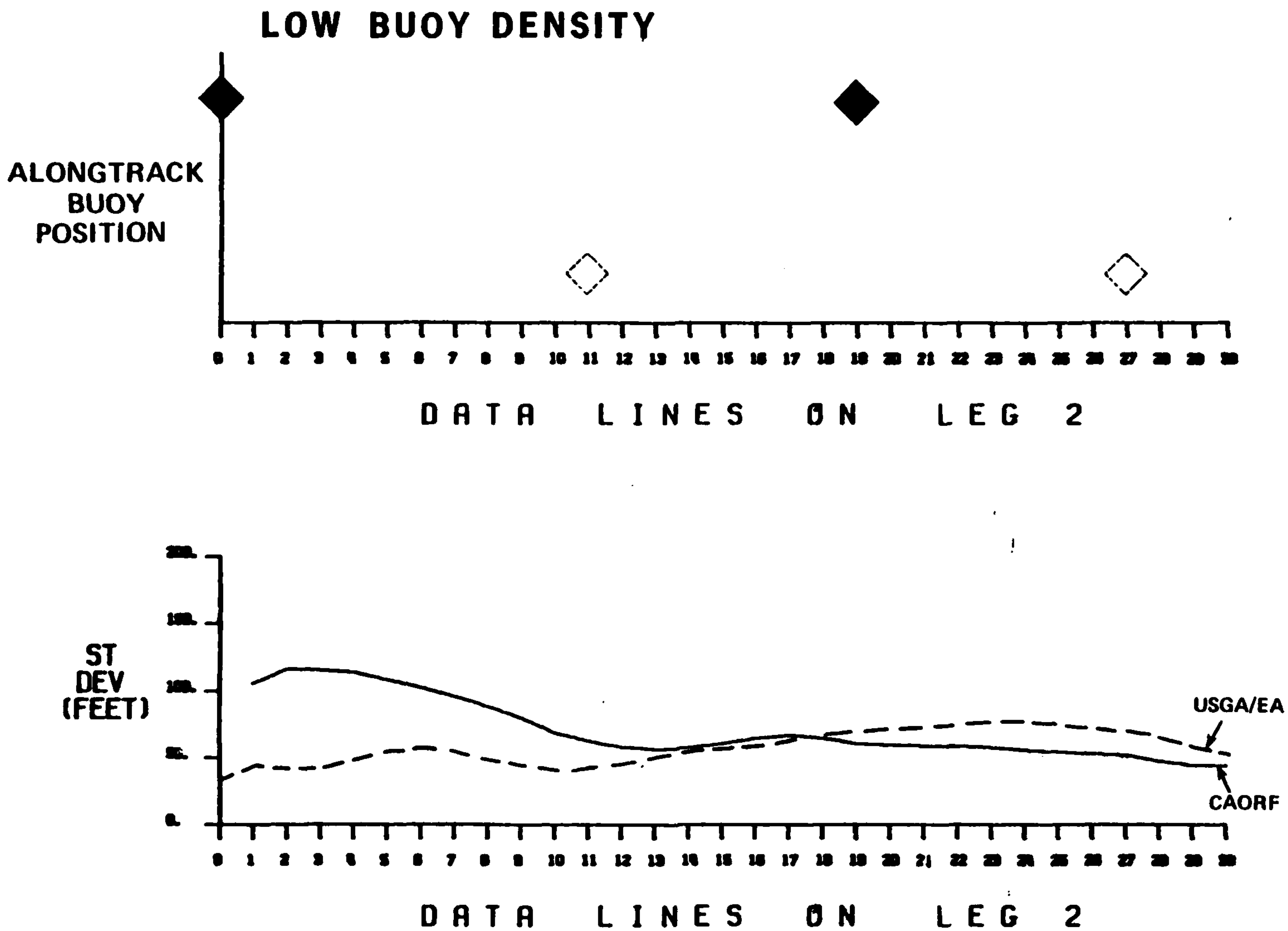
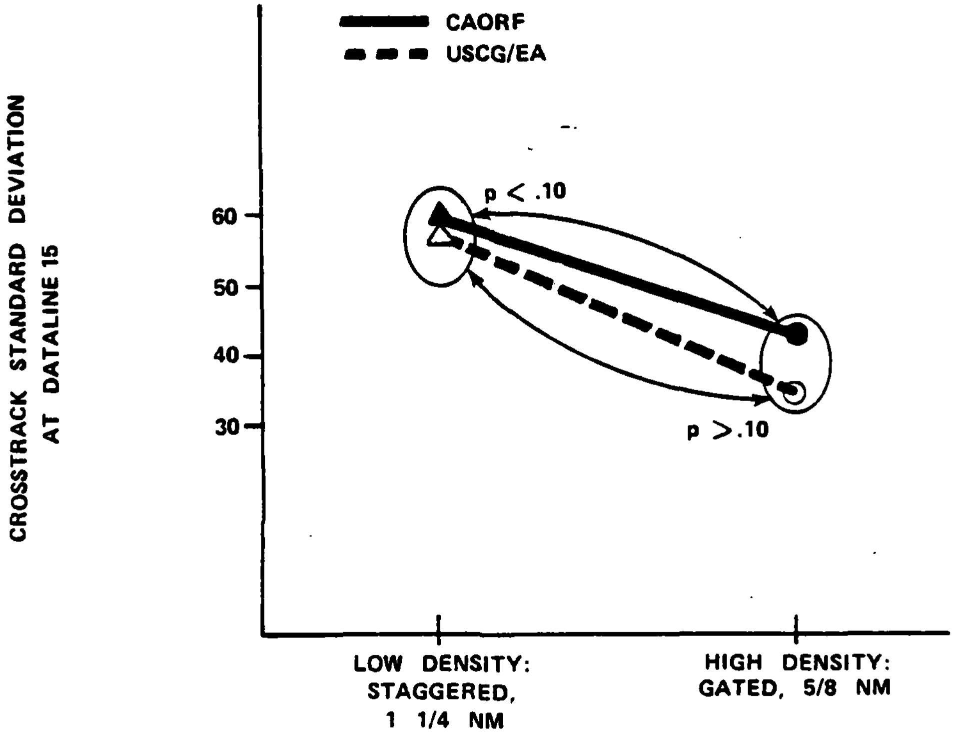


Figure 17. Performance in the Low Information Density Conditions for the Two Simulations



- CIRCLED VALUES ARE STATISTICALLY EQUIVALENT.
- VALUES JOINED BY ARROWS HAVE THE PROBABILITY INDICATED OF HAVING OCCURRED BY CHANCE.

Figure 18. The Interaction of Information Density and Simulation

can be considered the same for the purposes of this project. (This means a difference this large has a probability of more than 0.10 of occurring by chance alone. It could also be said that the two values fall within the same 0.90 confidence level.) The two simulations can be compared in terms of the differences between values obtained for conditions measured. The two values from the CAORF simulation – 61 and 43 feet – are different at the 0.10 level. The two values for the USCG/EA simulation do not quite reach the 0.10 level. For the CAORF experiment, the sample size for this comparison was 24, while the USCG/EA comparison was made with a sample size of 8. While the USCG/EA comparison is not quite different at the 0.10 level, it is so close that if the same difference had been obtained with a sample size of 9, it would have been significant.

Section 4

EFFECT OF INFORMATION DENSITY WITH THE TWO SHIPS

4.1 OVERVIEW

Performance with the 80,000 dwt tanker is generally poorer than that with the 30,000 dwt tanker. The poorer performance and the reasons for it are discussed in Section 5. The focus in this section is on the dependence of piloting performance on buoy information and on the relative dependence of piloting with the two ships on aids to navigation information. Topics discussed include the dependence of channel entrance performance on AN information; the dependence, or lack of dependence, of turn pullout performance on AN information: and differences between the ships in response to AN information for trackkeeping in Leg 2.

To summarize the findings of this section:

1.) Entrance To The Channel. There was no difference between levels of information for the 30,000 dwt tanker. For the 80,000 dwt tanker there was a difference. The larger ship requires a well-marked channel for its entrance.

2.) Turn Pullout. There was no difference between levels of information for the 30,000 dwt tanker, and only a slight difference for the 80,000 dwt tanker. However, there is evidence that potential effects were attenuated by the pilots' familiarity with the turn. It seems fair to conclude from earlier experiments and from other parts of the scenario in this experiment, that both ships, and especially the 80,000 dwt tanker, would have been helped — or would have needed — the high information density for the pullout.

3.) Trackkeeping with crosscurrent and crosswind. There was a difference in the precision of trackkeeping between levels of information with the 30,000 dwt tanker. Performance with the 80,000 dwt tanker was also improved by additional information. The combination of the larger ship, turn recovery, crosswind, and crosscurrent produced difficulties not ameliorated by additional information.

Both ships need high information density, but high information density does not solve the problem of handling a larger ship.

4.2 THE RELATIONSHIP TO OTHER EXPERIMENTS

The past experiments in this project have emphasized variations in aids to navigation placement while keeping the ship, and its characteristics, constant. The present experiment is meant to vary ships and ship characteristics. The ships and their physical and performance characteristics are described in Appendices A and B. Rather than holding aids to navigation placement constant, two different combinations were chosen to represent extremes among the conditions that have been used in the aids to navigation project. The high information density condition, illustrated in Figure 2, combined the favorable levels of three variables. They were:

1.) Straight channel marking: gated buoys.

2.) Spacing: 5/8 nm.

3.) Turnmarking: three.

The low information density condition, illustrated in Figure 3, combined the unfavorable levels of the same variables. They were:

1.) Straight channel marking: staggered buoys.

2.) Spacing: 1½ nm along one side.

3.) Turnmarking: one.

These straight channel differences — gates spaced at 5/8 nm and staggered buoys spaced at 1¼ nm along one side — could be viewed as a comparison of systems with equal alongtrack distances but with unequal buoy densities. However, the earlier CAORF and Channel Width experiments have shown that symmetry gives gates an advantage beyond their density. Therèfore, the difference between the two conditions included here is greater than would be implied by "unequal buoy densities." It is for this reason that the conditions have been labeled high and low information density. If the handling of the two ships differs in dependence on information to be had from the buoys, this extreme difference in information available maximized the chance that the difference would be revealed in performance.

4.3 THE CHANNEL ENTRANCE

The initialization conditions were different for this experiment than they had been for the earlier experiments. The start of the scenario was described in Section 1.3 and illustrated in Figure 6. The scenario began outside the channel to give the pilot the opportunity to acquaint himself with the ship by maneuvering it in "safe water" during his move into the channel. Once past the sea buoy, he was to move the ship to the centerline and trackkeep until ready for the turn. Since the straight channel segments to be entered were differently marked, it is possible to evaluate the effect of this marking on the entrance.

The ships differed in the degree of dependence on straight channel marking for their entrance. For the 30,000 dwt tanker the difference was slight. For the 80,000 dwt tanker there was a major difference that is illustrated in Figure 19. The distribution of transits is much wider for the low information conditions, skimming the edge of the channel as the pilots pass the sea buoy and find the centerline. For the high information conditions the distribution does not widen to the same extent nor stay as wide for as long a distance. The mean and standard deviations at data line 19, the maximum excursion for the 80,000 dwt tanker, are presented in Table 4. The difference in standard deviations is not significant at that data line while the values are at their maximum. The differences in standard deviations are significant at the 0.10 level from data line 17 to 13. (The F ratios become larger as the absolute values of the standard deviations decrease.) The mean for the low information condition does overshoot the centerline more for that interval but the difference is not significant there or at any point in Leg 1. As was the case for recovery from maneuvering tasks in earlier experiments, a gate ahead provides the best information for finding the centerline.

These data have implications for the design of aids to navigation systems; gated buoys are better than staggered buoys in guiding the pilot to a centerline track in a new channel, especially with a larger ship.

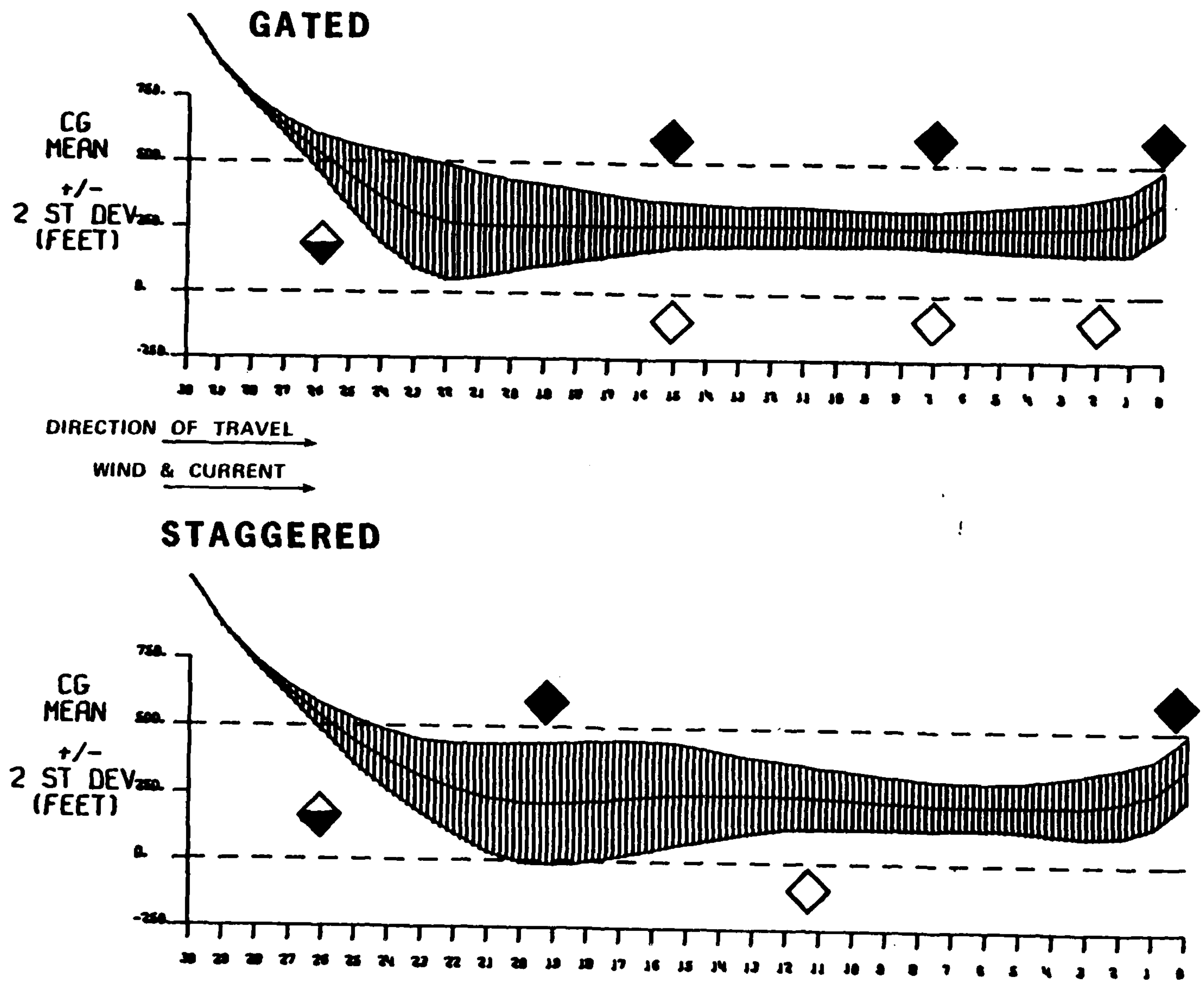


Figure 19. Marking and the Channel Entrance for the 80,000 DWT Tanker

TABLE 4. CHANNEL ENTRANCE PERFORMANCE AS A FUNCTION OF MARKING

CONDITION		Leg 1 Data Line 19 (feet)	Difference from CL (feet)	Leg 1 Data Line 17 (feet)	Difference from CL (feet)
30,000 dwt tanker,	Mean	286	36L	275	25L
High information	Standard deviation	57		36	
30,000 dwt tanker,	Mean	246	4R	252	2L
Low information	Standard deviation	57		46	
80,000 dwt tanker,	Mean	259	9L	261	11L
High information	Standard deviation	76		58	
80,000 dwt tanker,	Mean	214	36R	238	12R
Low information	Standard deviation	113		108	

<-->Probability less than .05 of occurring by chance.
L = Left
R = Right

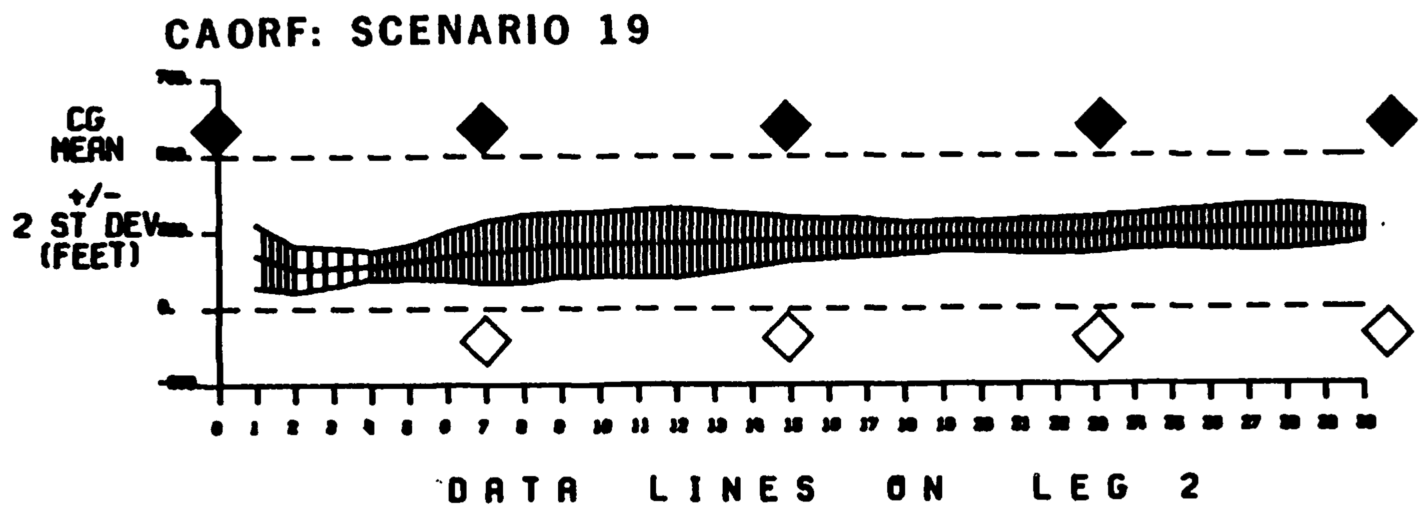
4.4 TURN PERFORMANCE

In the CAORF experiment, performance with the 30,000 dwt tanker in the turn pullout showed a dependence on buoy information that was not replicated here. Data from that earlier experiment are reproduced in Figure 20. (The high information density condition shown does not have the red pullout buoy that appears in the present experiment.) At CAORF the turn pullout is much better controlled with high information density. In the present experiment there is very little difference between the two information conditions for the 30,000 dwt tanker. This comparison for the present experiment is shown in Figure 21 and Table 5. Why was the dependence in the CAORF experiment not replicated in the present experiment? The reason seems to be a difference in the pilots' degree of familiarity with the turn. The CAORF subjects were both pilots who had been in other, but different experiments, and pilots who had never been on such a simulator or in an experiment before. Such naivete was not the case for the Ship Variables subjects.

The experiments done on the USCG/EA simulator provided a pool of data comparable over many conditions, but also created a pool of pilots who had a prepared response to the turn conditions that was independent of buoy information. The Channel Width and the three Radio Aids experiments used the same channel, turn, wind, current, ship, and speed. There were additional presimulation runs and consultations. Some of the pilots were in four or five experiments, or their equivalent, using the same channel conditions and ship. Their learning was not apparent until the comparison of turnmarking conditions in the present experiment. (The Channel Width experiment used only three-buoy turns.) That there are differences between information conditions for trackkeeping in Leg 2 implies the learning effect is confined to the turn. That there are differences between information conditions for the entrance to the channel implies that it does not transfer to new turn conditions. Dependence on buoy information can be evaluated in other parts of the scenario.

The familiarity of the local pilots with the turn conditions has implications for later experiments. The One-Sided Marking experiment, prepared but not run as of this writing, contains a turnmarking comparison made with the 30,000 dwt tanker. To avoid potential contamination to this comparison, only pilots that have been in a minimum number of experiments will be used. For the future Range experiment, the pilots familiar with the experimental channel provide a valuable resource. They provide the opportunity to evaluate the effect of local knowledge on turning from range to range. In the future, the effect of learning can be controlled by varying the pilots or the channel.

Information has more of an effect on the turn pullout with the 80,000 dwt tanker. The difference is illustrated in Figure 22 and summarized in Table 5. The distribution of transits with low information skims the edge of the channel, something that does not happen with high information. Neither the means nor the standard deviations are significantly different at even the 0.10 level. Performance with the 80,000 dwt tanker in the pullout is not as poor as was the case with the 30,000 dwt tanker at CAORF, suggesting there was some transfer of the learning effect at USCG/EA from the 30,000 dwt tanker to the 80,000 dwt tanker. Because of this learning effect, there are no major differences with either ship in the pullout. Generalizing from the CAORF findings, it seems fair to conclude that there would have been an effect of information without it. Differences in Leg 1 during the entrance into the channel suggest it would have been larger for the 80,000 dwt tanker.



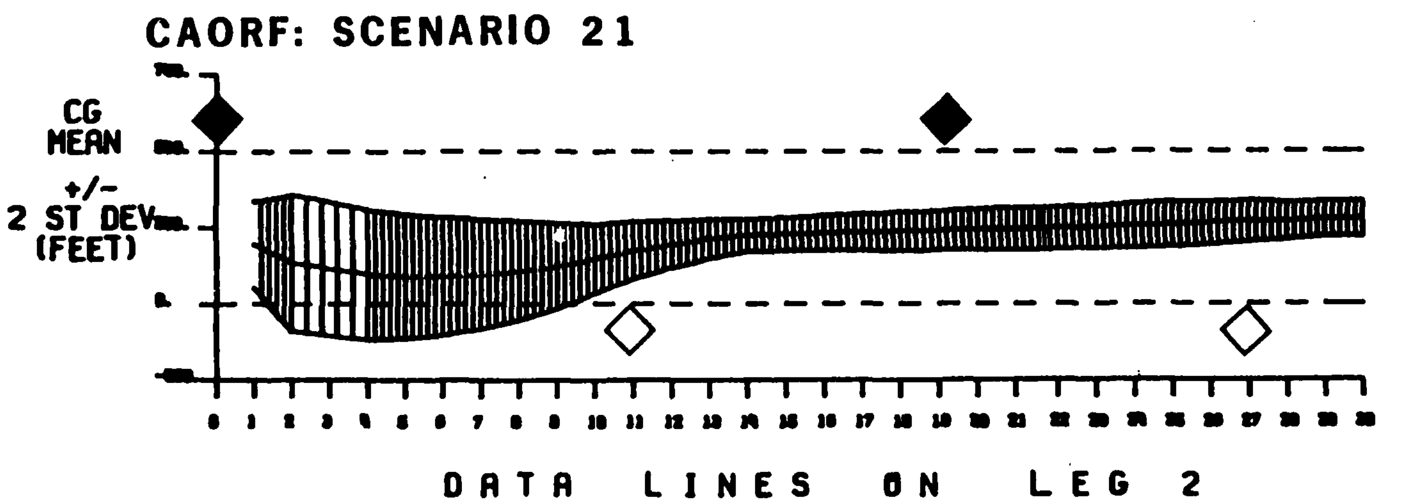


Figure 20. Marking and the Turn Pullout at CAORF

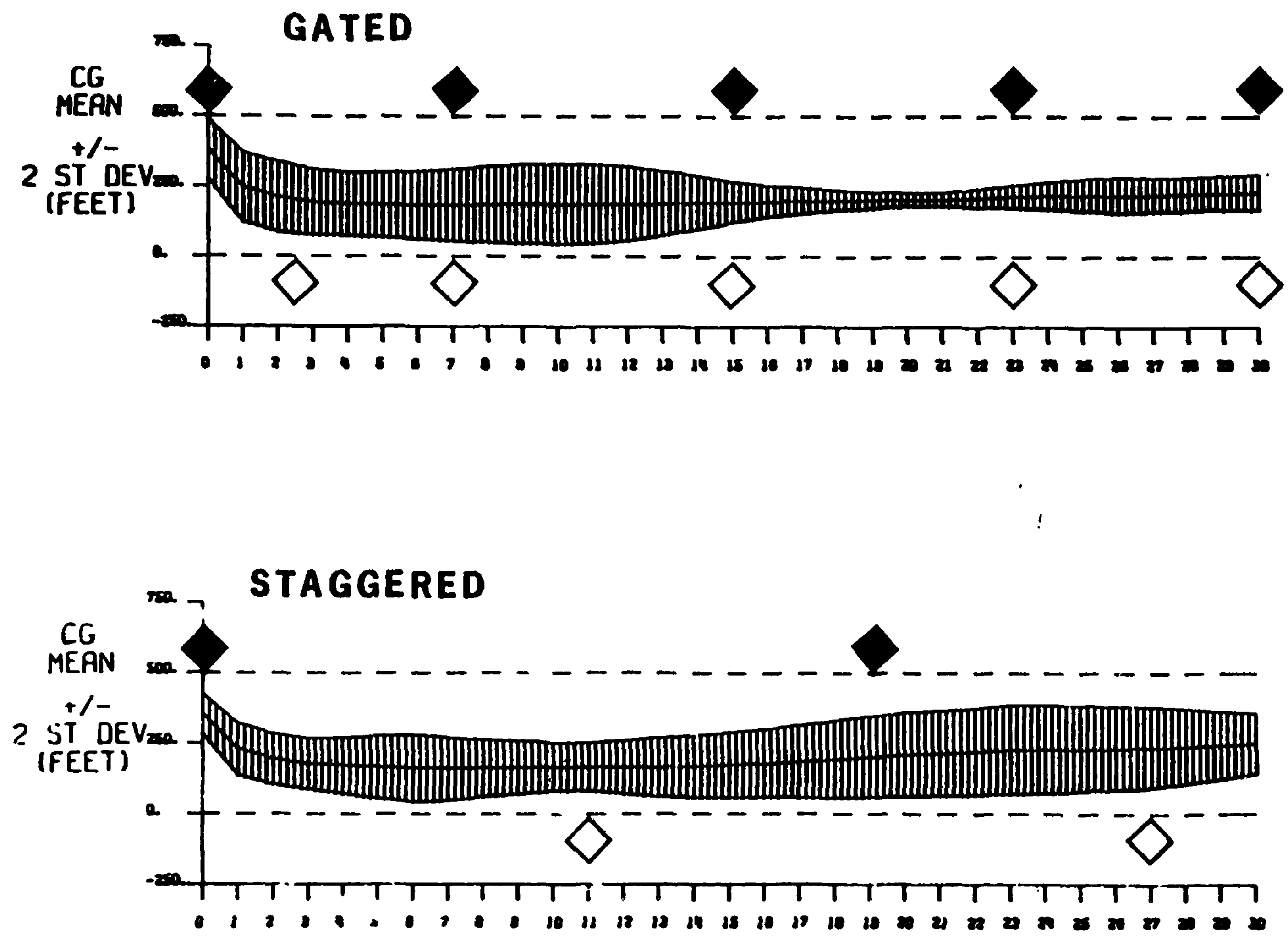


Figure 21. Marking in Leg 2 with the 30,000 DWT Tanker

TABLE 5. TURN PULLOUT PERFORMANCE AS A FUNCTION OF MARKING

CONDITION		Leg 2 Data Line 2 (feet)	Difference from CL (feet)
30,000 dwt tanker,	Mean	210	40R
High information	Standard deviation	62	
30,000 dwt tanker,	Mean	192	58R
Low information	Standard deviation	45	
80,000 dwt tanker,	Mean	138	112R
High information	Standard deviation	50	
80,000 dwt tanker,	Mean	126	124R
Low information	Standard deviation	69	

R = Right

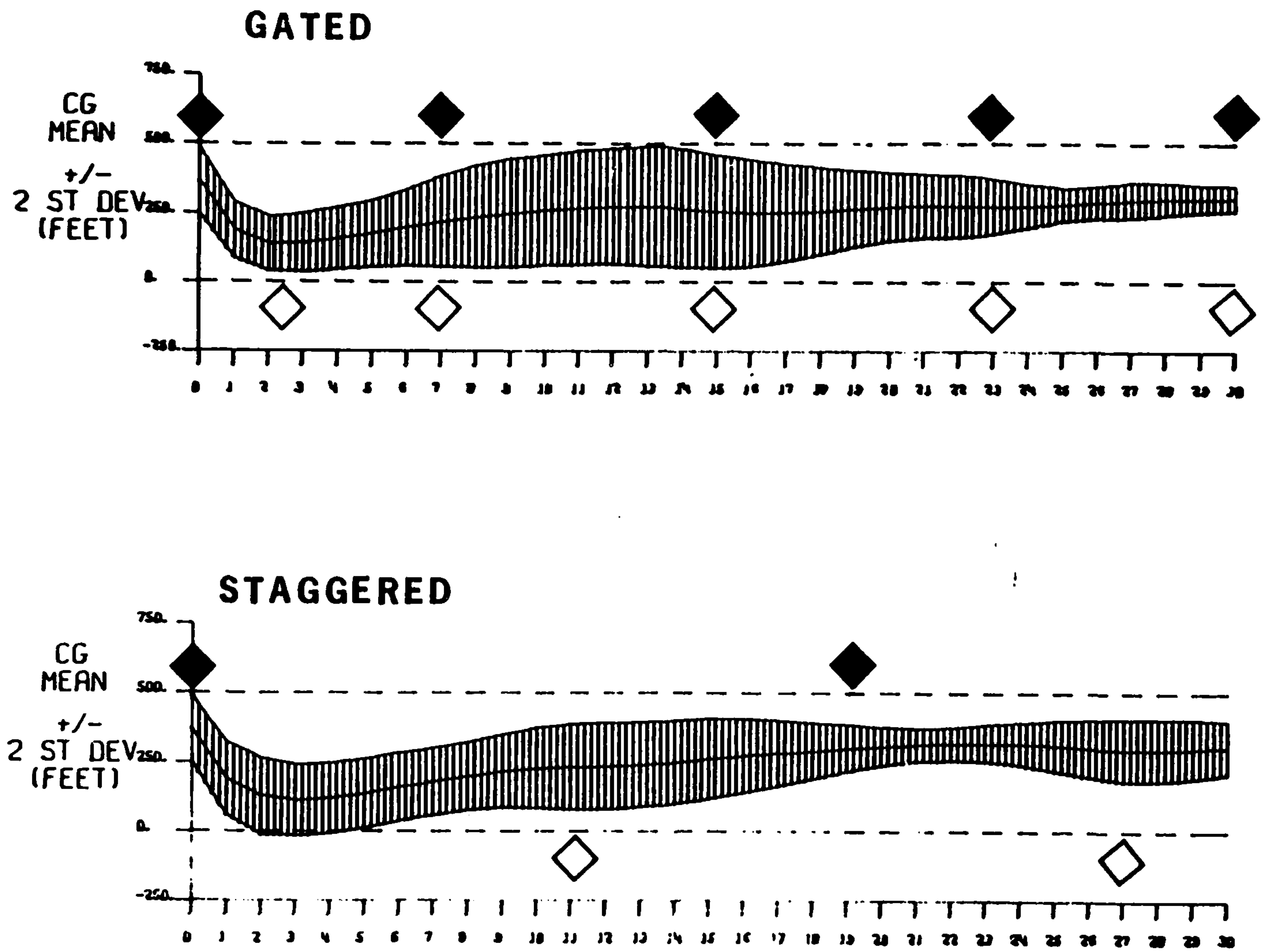


Figure 22. Marking in Leg 2 with the 80,000 DWT Tanker

4.5 TRACKKEEPING IN LEG 2

Performance with the 30,000 dwt tanker shows a dependence on information for trackkeeping in Leg 2 that is a replication of findings in earlier experiments. This dependence is illustrated in Figure 21. The selection of one data line to represent trackkeeping in Leg 2 with the drift angle made necessary by the crosscurrent, will simplify the discussion. Data line 15, which comes after apparent recovery from the turn at a point where the pilot sees two gates ahead in the high information condition and 2 buoys ahead in the low, seems an appropriate choice. This point, where the pilot has available the maximum trackkeeping information available in Leg 2, is an appropriate place to compare the two ship conditions in the use that can be made of this information. Values from data line 15 appear in Table 6. The means show little dependence on information. While the mean for the high information density condition is slightly closer to the centerline, the two are not significantly different from each other. They are both significantly different from a hypothetical mean on the centerline at either the 0.10 or 0.05 level of significance. Neither information condition puts the mean on the centerline for the 30,000 dwt tanker with the crosscurrent. Later in Leg 2, at data line 30, when the crosscurrent and the compensating drift angle have been reduced to zero, the means more closely approximates the centerline. There they are no longer significantly different from the centerline, even at the 0.10 level. They are not different from each other, as they were not at data line 15. The crosscurrent, and not the available information, controls the position of the mean.

There is a considerable effect on the width of the distribution, with the larger standard deviations for the low information condition. The standard deviations are significantly different at the 0.05 level from data lines 10 to 28. While they are not significantly different at data line 30, the standard deviation for the low information condition is still larger there. It is the standard deviation that reflects the effect of information density for the 30,000 dwt tanker. (Data from this comparison was selected for the evaluation of simulator differences in Section 3 and summarized in Figure 18. The point was made there that performance with the 30,000 dwt tanker responded to changes in information in this experiment as it had in earlier experiments.) Performance with the 80,000 dwt tanker in Leg 2 with two levels of information density is illustrated in Figure 22. Representative values taken at data line 15 appear in Table 6. The mean for the high information density condition is slightly closer to the centerline (250 feet), but this difference is not significant at the 0.10 level. Neither of these means are different from a hypothetical mean at the centerline. The means for the 80,000 dwt tanker approach the centerline more rapidly than was the case for the 30,000 dwt tanker. This does not mean performance was superior with the 80,000 dwt tanker. The crosstrack means of the transits for the two ships under high information density conditions are compared in Figure 23. The mean for the 80,000 dwt tanker crosses the centerline earlier, but then overshoots it. There is a constant difference of approximately 60 feet between the two means. At data line 30, the mean for the 80,000 dwt is different from the centerline, while that for the 30,000 dwt tanker is not. The position of the mean is controlled largely by crosscurrent, crosswind, and ship effects. Information density makes a relatively minor contribution.

The standard deviations at data line 15 are different with the two levels of information. That for the high information condition is higher. The difference is not significant at data line 15, but it is significant at the 0.10 level from data lines 19 through 22. (The size of the F ratio between the variances gets larger as the

TABLE 6. TRACKKEEPING PERFORMANCE IN LEG 2 AS A FUNCTION OF MARKING

CONDITION		Leg 2 Data Line 15 (feet)	Difference from CL (feet)	Significance of Difference (feet)
30,000 dwt tanker,	Mean	196	54R	p < .05
High information	Standard deviation	36		
30,000 dwt tanker,	Mean	174	76R	p < .05
Low information	Standard deviation	58		
80,000 dwt tanker	Mean	254	4L	-
High information	Standard deviation	101		
80,000 dwt tanker,	Mean	265	15L	-
Low information	Standard deviation	72		

CONDITION		Leg 2 Data Line ,30 (feet)	Difference from CL (feet)	Significance of Difference (feet)
30,000 dwt tanker,	Mean	231	19R	-
High information	Standard deviation	33		
30,000 dwt tanker,	Mean	252	2L	-
Low information	Standard deviation	53		
80,000 dwt tanker,	Mean	306	56L	p < .05
High information	Standard deviation	22		
80,000 dwt tanker,	Mean	309	59L	p < .05
Low information	Standard deviation	46		

R = Right

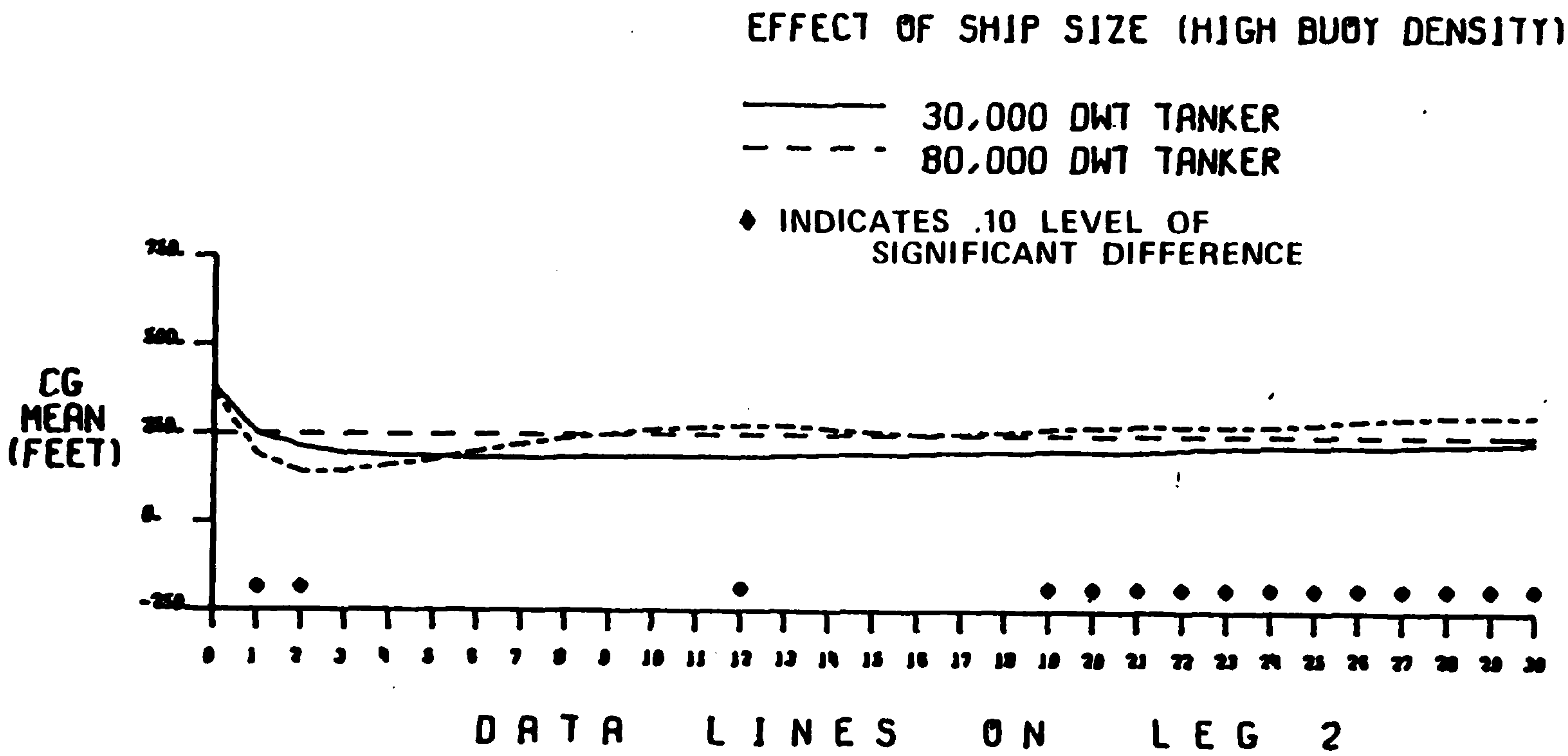


Figure 23. The Means in Leg 2 for the Two Ships

absolute values get smaller.) The slight improvement in the mean with the high information condition is paid for in an increased standard deviation during the recovery from the turn and the maneuvering toward the centerline.

Why does this combination of a (slightly) better mean and a (considerably) increased standard deviation shown in Figure 22 occur only with the 80,000 dwt tanker, only in the high information density condition, and only during the maneuvering segment of the leg? One possible explanation is in the strategies, or choice of strategies, the buoy arrangements allow. In the high information density condition, the gates allow a choice of strategies. To achieve the centerline in the new leg, the pilots can either find and approach it very early, as they pass through the first gate, or approach it more gradually, arriving at it only after recovery from the turn and the decrease in crosscurrent. If pilots split on which strategy to use, the results would show the better mean and increased standard deviation. The low information density condition does not allow such a choice of strategy. The only possible alternative is to steer toward the centerline further down the channel. The soonest the pilots would feel confident of the location of the centerline would be when they see it between two staggered buoys, about data line 15. The adaption by the pilots of this single strategy would result in the poorer mean and lower standard deviation. (The 30,000 dwt tanker performance illustrated in Figure 21 showed a tendency toward a larger standard deviation early in the leg with the high information density condition, but there the difference was not significant.) This association between a higher level of information and a larger standard deviation was also observed in the earlier Channel Width experiment. A large standard deviation must be interpreted with caution. It may not mean uncertainty of performance but a variety of strategies.

Later in Leg 2, the beneficial effect of information of performance with the 80,000 dwt tanker is simpler. At data line 30 with the centerline achieved, the standard deviation for the high information condition is lower than that for the low information condition. This difference is significant at the 0.10 level. This more expected effect of information on performance supports the interpretation that the higher standard deviation for the high information condition observed earlier in the leg was not the result of uncertainty.

In conclusion, increased information density improved trackkeeping performance unambiguously with the 30,000 dwt tanker. It improved performance for the 80,000 dwt tanker as well. Complications in performance with this larger ship suggest that the characteristics of the larger ship produce effects of larger magnitude than the information effects. The ship characteristics and their effects on performance are discussed in detail in Section 5.

Section 5

EVALUATION OF PERFORMANCE DIFFERENCES ATTRIBUTABLE TO DIFFERENCES IN INHERENT CONTROLLABILITY AND SHIP TYPE

5.1 INTRODUCTION

A principal objective of this experiment was to identify performance differences between two vessels under "perfect" aid to navigation conditions. The previous CAORF and Channel Width experiments had identified aid to navigation conditions and densities beyond which further improvements to performance would not be expected. Differences in performance under these conditions are presumably wholly due to differences in the inherent controllability and in the physical dimensions and design of the two vessels. If the magnitude of the piloting performance difference can be correlated with the magnitude of the differences in controllability, it will be feasible to extrapolate the performance differences for a wide variety of ships given only their inherent controllability characteristics. Extensive simulator evaluation of a large number of ship types will be unnecessary.

Experimental conditions run at various speeds with lower buoy densities provided within the experiment additional opportunity to evaluate the effect of changing selected inherent controllability characteristics. These runs were selected to isolate those characteristics which most affected piloting performance. Computer simulations of sea trials at various speeds and underkeel depths served to identify inherent controllability characteristics. Computer simulations were also used to extrapolate experimental findings regarding an untested variable: underkeel clearance.

This section discusses and analyzes the differences in piloting performance which may be attributed to the following factors:

- Ship type and size with perfect aids to navigation condition
- Ship speed
- Ship turning response differences
- Underkeel clearance

Appendix A presents a detailed discussion and definition of the inherent controllability differences between ships. It is suggested that the reader familiarize himself with this material prior to reading the remainder of this section.

The findings discussed in this section are as follows:

1) Ship Size: The data support a methodology by which piloting performance may be predicted from the inherent controllability of a vessel as measured in traditional sea trial maneuvers. Specifically:

The percent increase in crosstrack standard deviation between ships operating in narrow channels is approximately 1-1/2 times the average percent increase in the turn response (as measured in the distance domain) and track response variables for the 20/20 Z maneuvers between ships. (See Appendix A for definition of maneuvers and response variables)

Additionally:

Differences in piloting performance between two ships in channels with turn angles less than 35 degrees is not dependent on the differences in turning circle maneuvers.

This later finding suggests that posting turn circle responses on the bridge will be of little use to pilots in narrow waterway situations.

A further difference between vessels was a significant trend for the larger vessel to overshoot the desired track in the second leg:

Pilots tend to commence turns late for large ships (e.g. 80,000 dwt tanker) resulting in an overshoot of the desired track in the next leg.

2) Ship Speed: The expected improvement in maneuvering (turning) performance at higher speed does not occur. The improvement in turning response times does not encourage improved performance. Thus it appears.

High ship speed in narrow channels does not improve turning performance, especially so for large ships where performance may actually be slightly degraded at higher speed.

The single improvement with higher speed appeared to use a small improvement in trackkeeping performance when perturbed by cross winds and currents.

3) Underkeel Clearances: An extrapolation of the findings regarding ship size allows the formulation of the following hypotheses-based changes which occur in inherent controllability as underkeel clearances change. Based on an analysis of 20/20 Z maneuvers:

For piloting in narrow channels with turn angles equal to or less than 35 degrees, a small underkeel clearance is likely to be beneficial in reducing crosstrack standard deviations.

Based on the turning circle maneuvers, however

For transiting large angle turns, (angle exceeding 35 degrees) a small underkeel clearance is detrimental to achieving the desired mean track.

General Findings

The findings related to changes in the ship's inherent controllability indicate that the pilot's perception and decision process is highly dependent on the distance domain visual cues and the distance response variables of the ship. This finding supports an important generalization regarding placement of aids to navigation:

Aids to navigation should be configured so as to provide an adequate and frequent indication of crosstrack position in trackkeeping portions of a channel.

and

Aids to navigation should be configured so as to provide an adequate and timely indication of both crosstrack and alongtrack positions in the turning or maneuvering portions of a channel.

5.2 ANALYSES OF SHIP SIZE AND TYPE WITH PERFECT AIDS TO NAVIGATION INFORMATION

The principal physical differences noted in Appendix A are a midships wheelhouse with 45 foot height of eye (30,000 dwt) versus an aft wheelhouse with 80 foot height of eye (80,000 dwt).

The principal differences in the inherent controllability discussed in Appendix A occurred in the Z maneuver with little difference being observed in the turning circle maneuver. Table 7 summarizes the differences in these variables and the ratio of parameter values 80,000 versus 30,000 dwt ships. The ships physical dimensions are also tabulated.

Figures 24, 25, and 26 are reproduced from Appendix A to show the physical differences between the vessel dimensions.

Significantly the 80,000 dwt tanker response variables to the Z maneuver are greater than those for the 30,000 dwt. The average changes in response variables are noted in Table 8.

All response variables are typically 45 to 60 percent higher in value except for the turning maneuver (9 percent increase) and the heading response in the Z maneuver (5 percent increase). The conclusions of this comparison are that observed performance differences are likely attributable to differences in the turn responses (time and distance domain) and the track response of the Z maneuver.

Performance with the two ships was evaluated in the channel marked with a high density of buoys, i.e., "perfect information." Figure 27 shows the channel segments used. They are marked with gated buoys spaced at 5/8 nm with three buoys at the turn.

TABLE 8. AVERAGE CHANGES OF INHERENT CONTROLLABILITY FOR THE 80,000 DWT VERSUS 30,000 DWT TANKER, 6 KNOTS, SHALLOW WATER

20/20 Z MANEUVER	%Increase
Turn response (time domain)	60
Turn response (distance domain)	56
Heading response	5
Track response	46
TURNING CIRCLE MANEUVER	
Average response change	9

TABLE 7. COMPARISON OF INHERENT CONTROLLABILITY FOR AN 80,000 AND 30,000 DWT TANKER: 6 KNOTS, 1-FOOT UNDERKEEL CLEARANCE

20/20 Z MANEUVER		30,000 dwt	80,000 dwt	Ratio
Turn Response Variables				80/30
Rise time: T_{20}	(Seconds)	110	150	1.40
Heading lag: $T_{\psi lag}$	(Seconds)	30	60	2.00
Displacement lag: T_{Dlag}	(Seconds)	160	260	1.63
1/max slew rate: $1/\dot{\psi}_{max}$		4 sec/deg	5.6 sec/deg	1.38
Distance travel for: T_{20}	(Feet)	1097	1476	1.34
Distance travel for : $T_{\psi lag}$	(Feet)	292	559	1.91
Distance travel for: T_{Dlag}	(Feet)	1546	2356	1.62
Distance travel for max heading change		38.5 ft/deg	52.6 ft/deg	1.37
Heading Response Variables				
Max heading excursion: ψ_{max}	(Degrees)	24.4	24.8	1.01
Heading overshoot: % ψ_{os}	(Percent)	22	24	1.09
Track Response Variables				
Max crosstrack excursion: D_{max}	(Feet)	533	810	1.52
Crosstrack overshoot: $\%D_{os}$	(Percent)	330	459	1.39
TURNING CIRCLE MANEUVER (35 deg rudder)				
Tactical diameter	(Feet)	3625	3753	1.04
Advance	(Feet)	2114	2496	1.18
Transfer	(Feet)	1700	1790	1.05
PHYSICAL PARAMETERS				
L.O.A.	(Feet)	596	763	1.28
Beam	(Feet)	84	125	1.49
Displacement	(Tons)	39,000	100,000	2.56

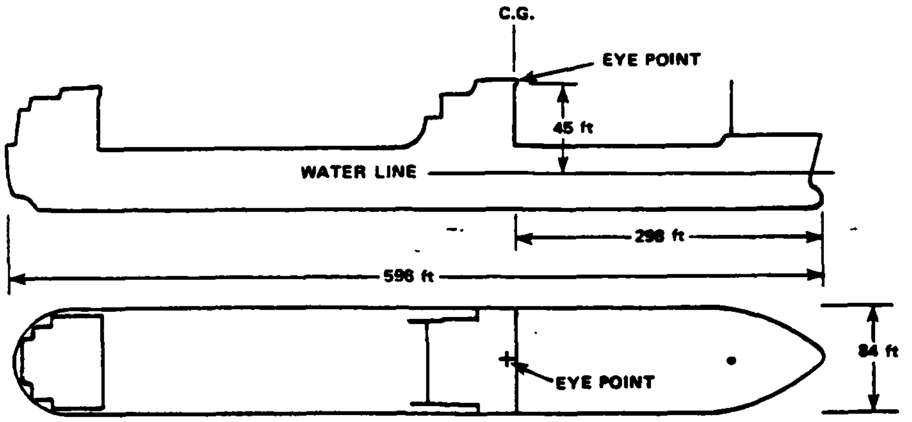


Figure 24. Plan and Elevation of a 30,000 DWT Tanker

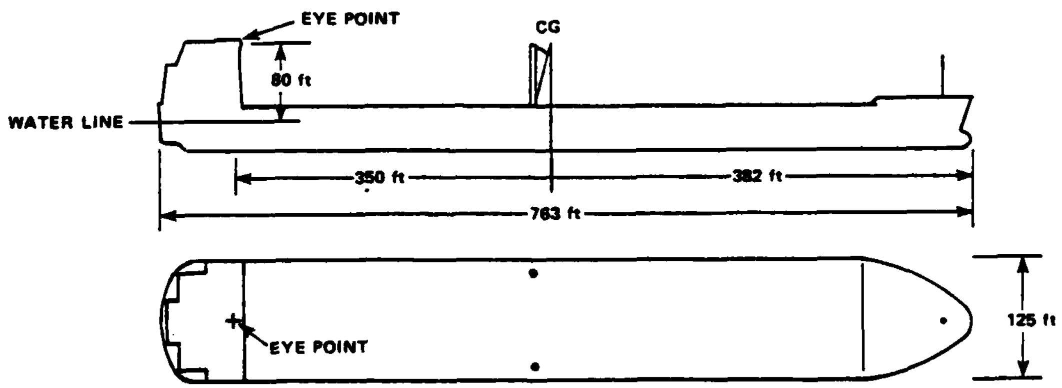


Figure 25. Plan and Elevation of an 80,000 DWT Tanker

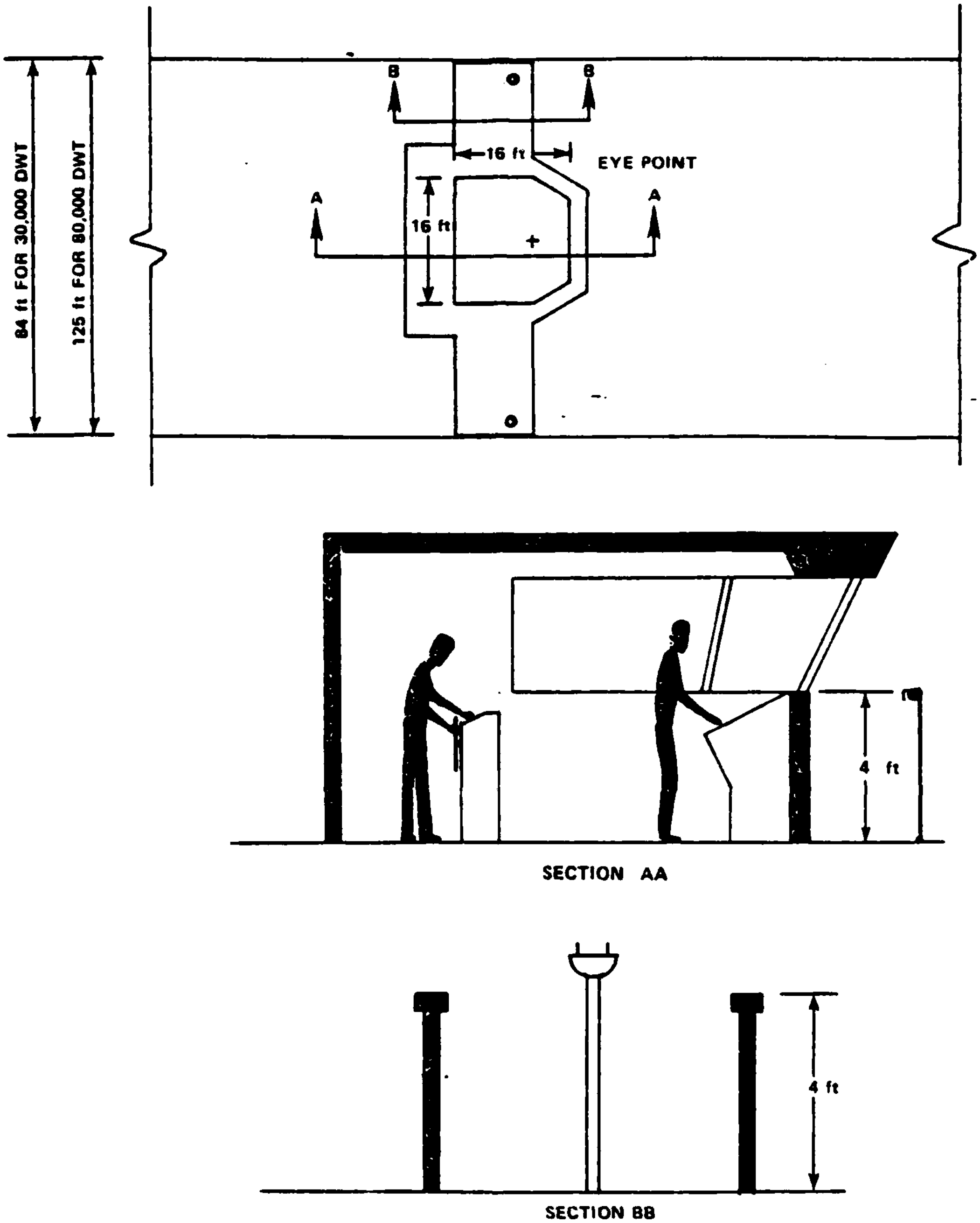


Figure 26. Plan and Sections for Wheelhouse with Bridge Wings on 30,000 DWT Tanker

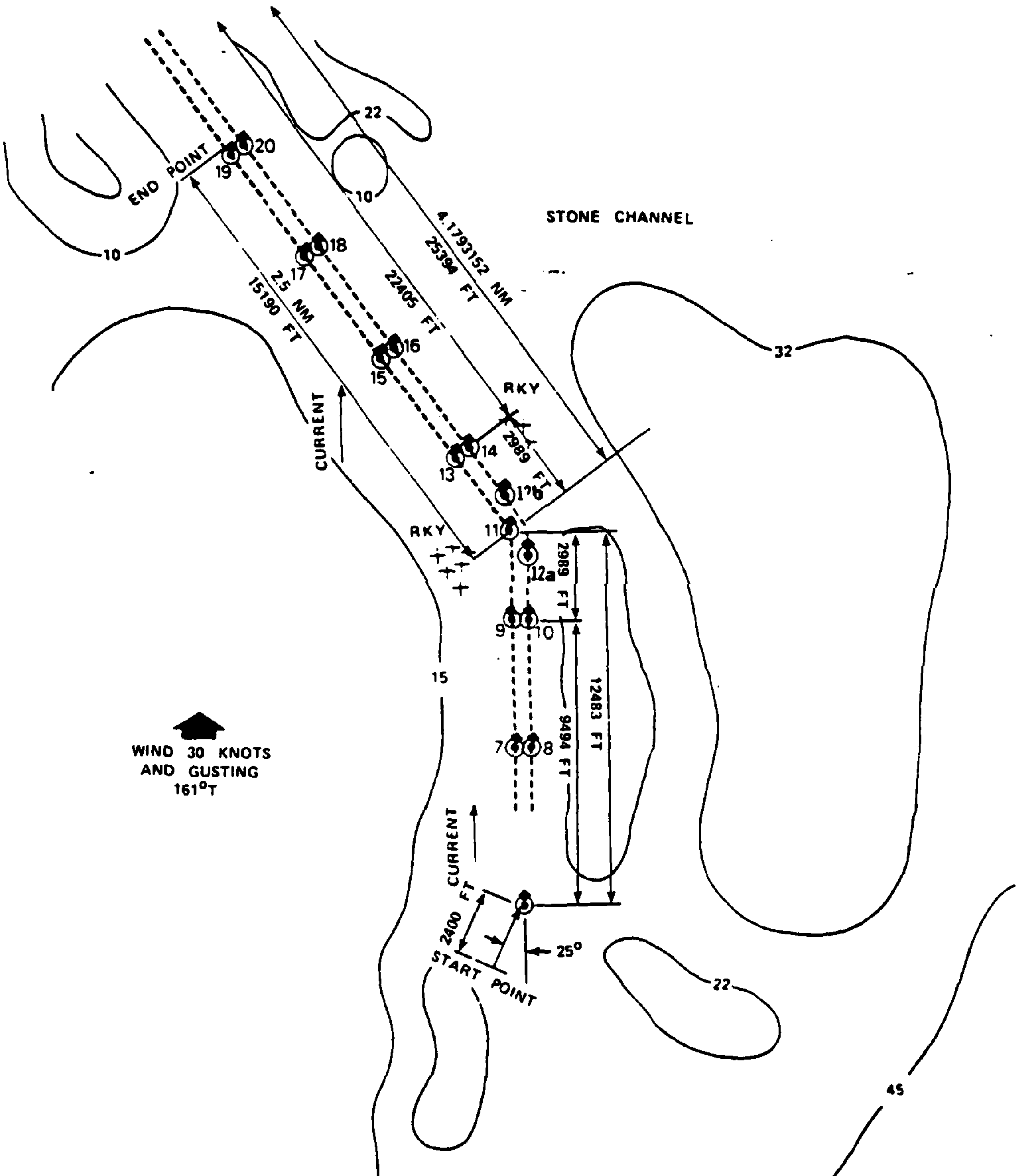


Figure 27. Chart 1 - High Information Density

Piloting performance differences between the two vessels is shown in the combined track plots in Figure 28. These plots are shown as a continuous linear plot with the turn having occurred at data line 0. The data depict the mean track +/- 2 standard deviations in the crosstrack direction. This envelope typically encloses 95 percent of the ships' tracks observed in the experiment. Data are plotted for every data line where data lines are 475 feet apart.

Figure 28 indicates that both ships were piloted successfully under these conditions since the combined plots fall within the channel boundaries. These data, however, indicate that there is a general increase in crosstrack variations for the 80,000 dwt vessel. Detailed comparison of the two conditions in both mean crosstrack location and standard deviations is shown in Figure 29. These data indicate that there is a significant increase in the standard deviation for the 80,000 dwt tanker which occurs along most of the channel length. Additionally, the mean crosstrack location appears to be significantly different in several regions of Leg 2. These differences are discussed by regions associated with the different maneuvering problems.

Behavior differences in Leg 1 are confined to Region 1, indicated in Figure 29. A statistically significant, 65 percent increase in crosstrack standard deviation is noted for the 80,000 dwt tanker in Table 9. No significant difference in mean location is present. This difference occurs under the unique condition of the wind and current perturbing conditions being directly aft of ownship. In this leg the pilot was permitted to align the ship perfectly to the axis of the channel and "split" the buoy gates with the ship's jackstaff, a perceptual task in piloting which has previously been identified to be one of the most accurate in the CAORF experiment. The increased standard deviation in this region and its consistent value for the next 6175 feet (data lines 15 to 2) supports the conclusion that this increase in crosstrack standard deviation is totally attributable to differences in inherent controllability. Note particularly that the midships versus aft wheelhouse and the 45 foot versus 80 foot height of eye differences would have negligible effect on the process of "splitting" gates with the jackstaff. It had been established earlier in the CAORF experiment and discussed in Appendix A that the perceptual processes which might be aided by height of the eye (i.e. perception of the slope of the channel edge relative to the horizon) was not a predominant process and if there were an important process, the 80,000 dwt tanker with a higher height of eye would be favored potentially reducing the standard deviation for the larger ship.

Region 2 shown in Figure 29 indicates performance in the immediate vicinity of the turn. Interestingly, a significant difference occurs in the mean tracks exiting the turn. There appears to be no significant difference in the crosstrack standard deviations. The difference in mean location may result from three sources: failure to commence the turn sufficiently early, differences in inherent maneuverability, and differences in wheelhouse location. Upon closer examination, it is likely that both the aft wheelhouse and the inherent controllability of the 80,000 dwt ship contribute to the failure to commence the turn early. The differences in turn initiation are evident when comparing the mean positions at data lines 3, 2, 1, and 0 of Leg 1 and the mean tracks shown in Figure 30. The 30,000 dwt tanker appears to have established a higher crosstrack velocity in the direction of the turn between data lines 1 and 0. The 80,000 dwt tanker, while drifting left as it approaches the turn, has developed less of a crosstrack velocity between data lines 1 and 0 and must in essence complete most of its turn after it passes the turn apex. This late turn results in an overshoot of the Leg 2 centerline and the significant difference in mean track lines.

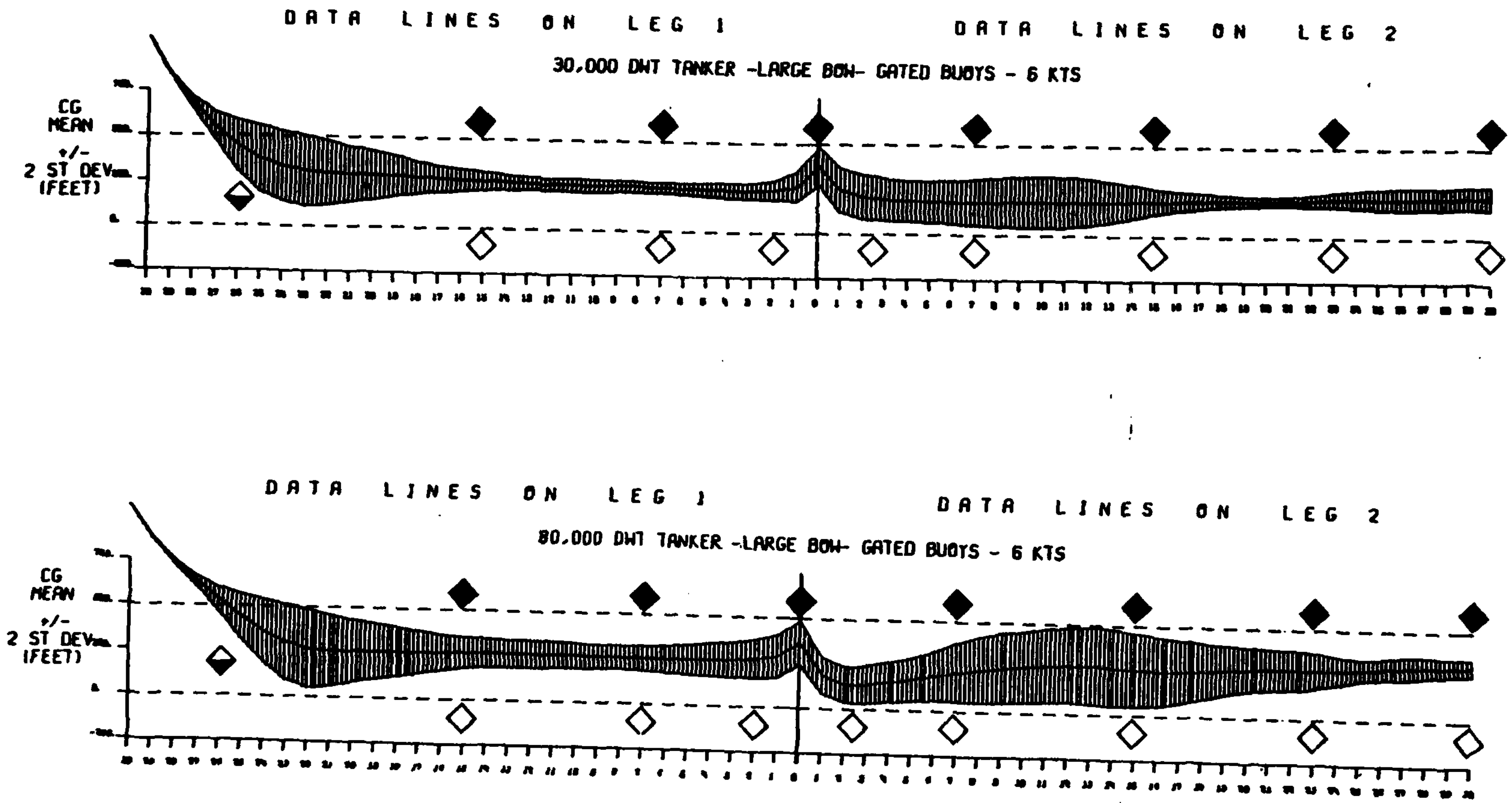


Figure 28. Combined Plots of Piloting Performance 30,000 vs 80,000 dwt Tanker, 6 KTS, Perfect Information

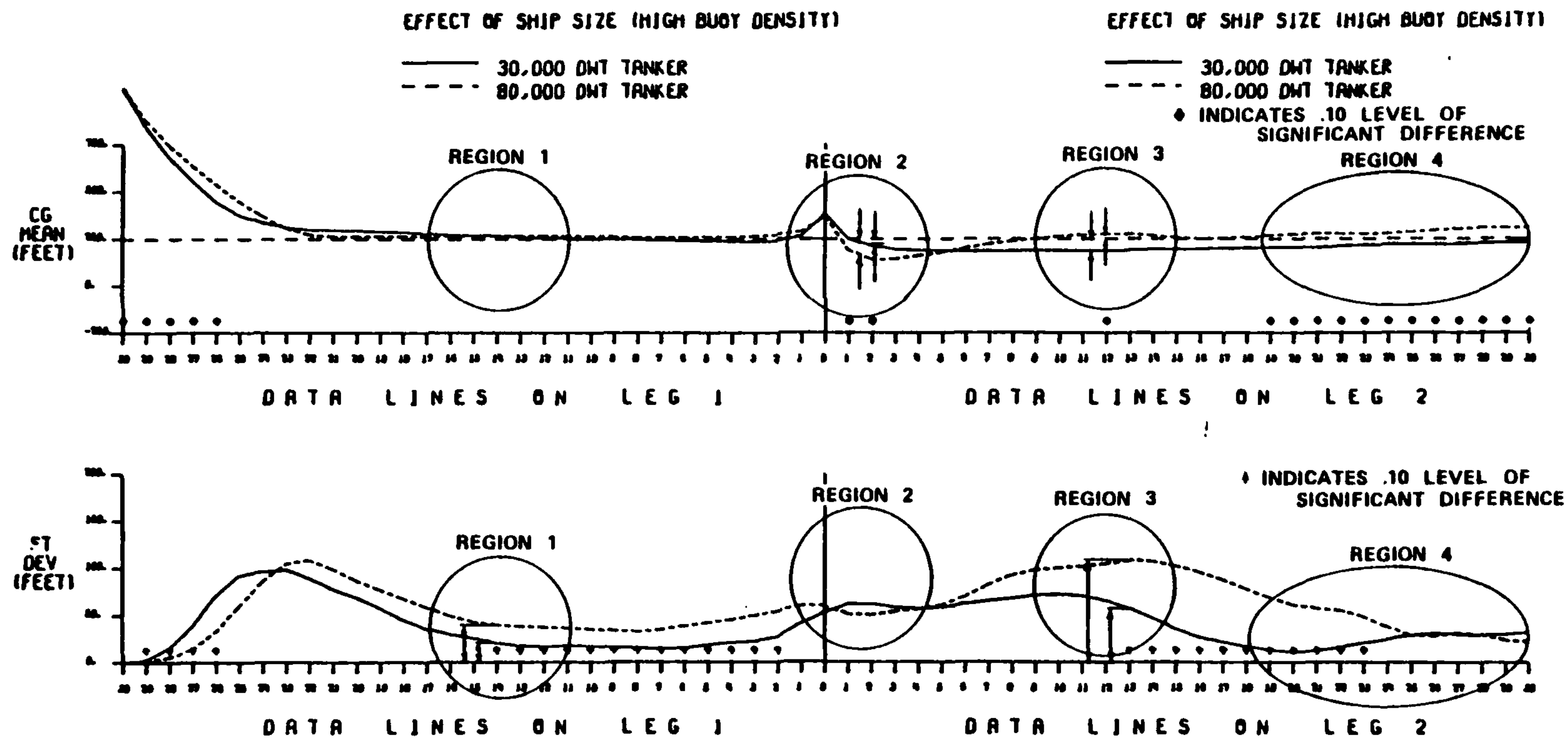


Figure 29. Crosstrack Mean and Standard Deviation of Piloting Performance, 30,000 vs 80,000 dwt Tanker, 6 Kts, Perfect Information

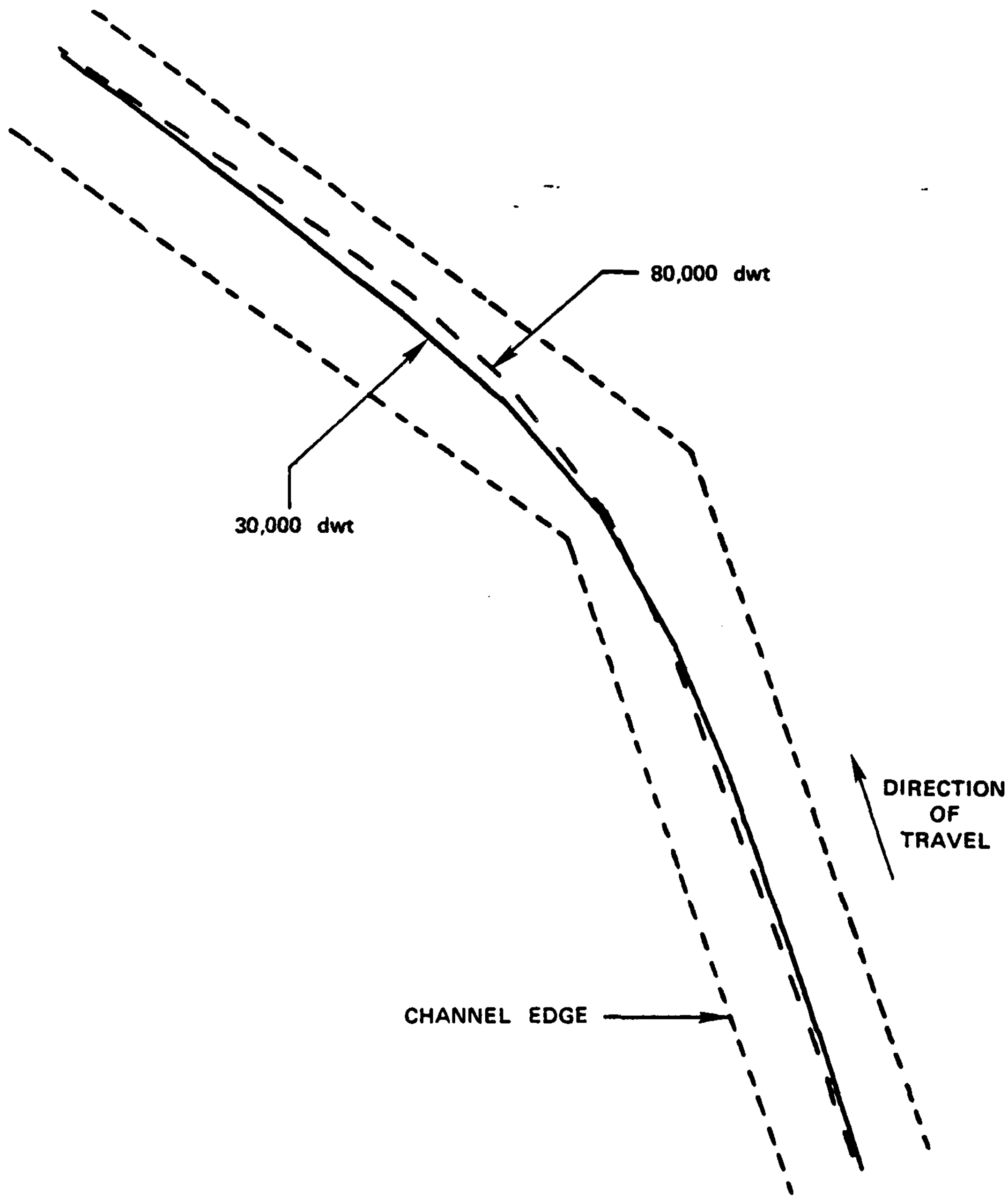


Figure 30. Mean Tracks In A 35-degree Turn 30,000 vs 80,000 dwt Tankers, 6 Kts, Perfect Information

TABLE 9. CROSSTRACK PERFORMANCE DATA, SHIPS' CG, 30 vs 80,000 DWT TANKERS, 6 KTS., PERFECT INFORMATION

	MEAN CROSSTRACK POSITION	
	30,000 dwt	80,000 dwt
Region 1 (feet)	Same	
Region 2 (feet)	40 (R)	112 (R)
Region 3 (feet)	59 (R)	25 (L)

R = right
L = left

	Standard Deviation Crosstrack Position (feet)		80 vs 30 % Increase
	30,000 dwt	80,000 dwt	
Region 1	26	43	65
Region 2	Same		
Region 3	57	108	89

The aft wheelhouse may contribute to the late initiations of the turn. The pilot located aft of the ship's center of gravity must initiate the turn at a greater absolute distance from the turn apex buoy versus the midships wheelhouse located at the center of gravity. Previous distance estimating experiments further concluded that at greater distances from turn buoys the mean error in distance estimation was greater and that the pilots tended to estimate their position to be further from an aid than was the actual case.[11] Thus, the tendency in the aft wheelhouse ship would be to wait till the aid was perceived to be sufficiently close, then maneuver (resulting in a late turn initiation).

The problem with the 80,000 dwt tanker is further aggravated by its slower turn response in the distance domain (see Table 7). The 80,000 dwt will travel a greater distance after helm changes prior to achieving the desired heading angle or response. The distance traveled for the 80,000 dwt vessel is 400 to 800 feet greater than for the 30,000 dwt vessel. This distance aggravated by the aft wheelhouse location and an increased perception error required the pilot to initiate his turn maneuver 800 to 1200 feet earlier as he approached the turn. This would seem to be of sufficient magnitude to account for the tendency for the larger ship to maneuver late. It is interesting to note that this argument would also explain an increase in crosstrack standard deviation for the 80,000 dwt vessel which did not occur. The explanation for this appears to lie in the fact that the channel was well marked and in order not to leave the channel once the pilots overshot the turn, they consistently maintained the ship's position along the outside of the channel. Note that the combined plots for the 30,000 dwt vessel follow the outside edge of the channel for a substantial distance, 6175 feet (lines 2 to 15) in Leg 2.

[11] Eclectech Associates, Inc. "Restricted Waterways Experiment IIIB Results and Findings." U.S. Maritime Administration and U.S. Coast Guard, Washington, D.C., May 1978.

The turn recovery and initial maneuvering in a crosscurrent and wind are shown in Region 3 of Figure 29. Significant trends are observed in the mean positions at data line 12 and the differences in the standard deviations. The 80,000 dwt vessel has returned to the centerline while the 30,000 dwt is displaced from the channel centerline 62 feet to the left. Similar to Leg 1 the crosstrack standard deviation for the 80,000 dwt vessel is larger than that for the 30,000 dwt vessel. (See Table 9.)

The interesting fact is that the center of gravity of the 80,000 dwt tanker is closer to the channel centerline. The displaced mean for the 30,000 dwt vessel was expected as it had been observed in the CAORF and Channel Width visual experiment conducted under equivalent conditions. The good performance of the 80,000 dwt was not expected. In analysis, the difference in mean positions is not likely due to differences in inherent controllability but rather physical and perceptual differences. The improved performance likely occurs as a result of either the aft wheelhouse location or the increased height of eye. Considering the fact that both vessels have a drift angle to compensate for the crosscurrent, the pilot's ability to center the 80,000 dwt more precisely must rely upon his ability to perceive the ship's position relative to the channel edges. It is believed that his improved performance is dependent wholly upon the aft wheelhouse location. While many subtle perceptual differences exist between the midships and aft wheelhouse, the advantage of the aft wheelhouse may lie in the fact that the entire ship can be observed from the aft wheelhouse and thus its position in the channel more easily observed. (See Appendix A, section A.2 for a more detailed discussion of perceptual differences.) Only the forward half of the ship may be observed with a midships wheelhouse.

The 89 percent increase in the crosstrack standard deviation for the 80,000 dwt vessel may be mostly attributable to the differences in inherent controllability and also to the attempts by the pilots to reachieve the centerline position having overshot the turn. This appears to be a difficult task with an 80,000 dwt vessel because the peak variation occurs over a mile from the turn apex (line 13). Comparison of the standard deviations between vessels indicates the 30,000 dwt vessel is brought under consistent control in Leg 2 within 1-1/4 nm of the turn (Line 15). The 80,000 dwt vessel, however, requires almost 2 nm (Line 25) to achieve consistent control. This distance represents a 60 percent increase in alongtrack distance.

The trackkeeping performance for Leg 2 is indicated in Region 4. The differences in mean tracks appear as a parallel offset which remains approximately equal in magnitude to that discussed for Region 3. Both mean tracks appear to drift from right to left. The differences in the crosstrack standard deviations in Region 4, while different at a statistically significant level, reflect actually different problems for the two ships. As discussed above, the 30,000 dwt vessel is trackkeeping, having recovered from the turn while the 80,000 dwt vessel is still recovering from the turn maneuver.

The interesting property of the mean tracks is the drift from right to left between Lines 12 and 30. This behavior had been related to the magnitude of the crosscurrent component in this region in the CAORF experiment. This drift had been nicely explained to be the result of the reduction in the ship's drift angle from 4 degrees at Line 12 to 0 degrees at Line 30. This explanation does not, however, explain why the 80,000 dwt mean tracks would be near the centerline at Line 12 but 56 feet left at the end of the leg, Line 30. A clue to the probable source for this behavior is the fact that the rate of lateral set remains constant along the leg. The

effect is more likely, therefore, related to constant perturbation, the wind. The lateral set can be explained as "walking" which results from wind-inducted, turning moments to the left. This phenomenon had been hypothesized to occur in an earlier simulator experiment.[12] It results from the helmsman, independent of the pilot, seeing a tendency from the ship to always rotate left while attempting to hold course with the rudder amidships. The helmsman will counter this rotation by applying a small right rudder occasionally or by attempting to maintain a right biased rudder. The net effect, however, is that the ship rotates more often to the left of the ordered course and the resultant mean track exhibits an average lateral set which is evident in the mean tracks. Further evidence to support this hypothesis is presented in section 5.3 which discusses speed effects.

While the wind effects adequately describe the lateral set in the mean tracks, they do not account for the fact that the 80,000 dwt commenced trackkeeping near the centerline at Line 12 and diverged from the centerline to a position 56 feet to the left of the centerline at the end of the leg. A possible explanation of this characteristic is that there exists a band of either perceptual insensitivity as to the actual location of the centerline or there is a region of channel which is considered to be the "center" of the channel and it lies approximately ± 60 feet from the centerline. It is likely that the later explanation is valid. Under perturbing conditions (crosscurrents and winds) the pilots attempt to achieve a position near the channel centerline and hence null the perturbing conditions. This process results in data which indicate the pilots are satisfied with mean tracks near the centerline. Note that with no perturbing conditions in Leg 1, both ships achieved mean tracks very close to the centerline. The width of the channel "center" appears to be dependent on the perturbations to the trackkeeping function. A longer channel in Leg 2 would be required to identify the edge of the channel center, i.e., the position at which the pilot would correct the vessel's wind-induced lateral set.

Given all of the above differences, the major contributing factor to differences in piloting performance appears to be differences in inherent controllability. It is important to note that the percent changes in 20/20 Z maneuver response variables (increases of 45 to 60 percent) are similar to the percent changes in the crosstrack standard deviations in Leg 1 and 2 (increases of 65 to 89 percent). On the average, *the percent increase in crosstrack standard deviations between ships is 1-1/2 times the average percent increases in the turn response and track response variables of the 20/20 Z maneuvers.*

This generalization appears to fulfill the experimental objective of identifying a method of predicting piloting performance of various ships based on their inherent controllability parameters.

5.3 ANALYSIS OF THE EFFECT OF SHIP'S SPEED

An hypothesis of the experimental design was that increased ship's speed would improve shiphandling performance. This belief was based on the fact that the ships' inherent controllability seemed to improve with increased speed. Further, it was hypothesized that the higher rate of motion of visual information might improve perception of ownship's motion relative to the channel.

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[12] Ibid.

This hypothesis was tested for both the 30,000 dwt and the 80,000 dwt tanker. Each ship was run at 6 and 10 knots in a low density buoy configuration. Low density was selected to represent the "worst realistic case" for aids to navigation configurations. Findings would therefore be applicable to all practical configurations. It was believed high buoy density channels would provide sufficient control such that differences would be masked.

Computer simulation of sea trial maneuvers facilitated a comparison of the changes which occur in inherent controllability as a result of increased speed. Tables 10 and 11 list the response variables for the 30,000 dwt and 80,000 dwt vessels respectively at 6 and 10 knots. The ratios of variables provide an indication of the changes in the variables as a function of speed. Table 12 summarizes the average change in each variable group for both the 30,000 dwt and 80,000 dwt ship. These data indicate that the only significant change occurs in the turn response variables measured in the time domain, i.e., 35 to 38 percent decrease in response times. All other variables change a lesser amount including the turn response measure in the distance domain (4 to 7 percent increase). These data indicate that increased speed changes only the time-based rate of change of maneuvers. The tracks of the ships remain essentially the same at both speeds. At higher speeds the ships simply move along their respecitve tracks faster for identical maneuvers. Observable changes in performance (if any) are thus attributable to the increased rate of change of visual information, not to significant changes in the track related factors of inherent controllability.

The channel configuration utilized to test speed effects is shown in Figure 31 for reference. These markings were considered marginally adequate for operations in 1-1/2 nm visibility during the day. It was expected that even without a 3-buoy turn the performance of the 30,000 dwt ship would be adequate.

TABLE 12. AVERAGE CHANGES OF INHERENT CONTROLLABILITY FOR 10 KNOTS VERSUS 6 KNOTS FOR A 30,000 DWT AND 80,000 DWT TANKER, 1-FOOT UNDERKEEL CLEARANCE

20/20 Z MANEUVER	30,000 dwt	80,000 dwt
	% Change	
Turn response (time domain)	35 (decrease)	38 (decrease)
Turn response (distance domain)	7 (increase)	4 (increase)
Heading response	16 (increase)	13 (increase)
Track response	11 (increase)	7 (increase)
TURNING CIRCLE MANEUVER		
Average Response Change	4 (increase)	4 (increase)

TABLE 10. COMPARISON OF INHERENT CONTROLLABILITY FOR A 30,000 DWT AT 6 AND 10 KNOTS; 1-FOOT UNDERKEEL CLEARANCE

20/20 Z MANEUVER	30,000 dwt	30,000 dwt	Ratio
Turn Response Variables	6 knots	10 knots	10/6
Rise time: T_{20} (sec)	110	69	0.63
Heading Lag: $T_{\psi lag}$ (sec)	30	21	0.70
Displacement Lag: T_{Dlag} (sec)	160	101	0.63
1/max slew rate: $1/\dot{\psi}_{max}$	4 sec/deg	2.5 sec/deg	0.63
Distance travel for: T_{20} (feet)	1097	1140	1.04
Distance travel for: $T_{\psi lag}$ (feet)	292	336	1.15
Distance travel for: T_{Dlag} (feet)	1546	1601	1.04
Distance travel for max heading change	38.5 ft/deg	40 ft/deg	1.04
Heading Response Variables			
Max heading excursion: ψ_{max} (degrees)	24.4	25.6	1.05
Heading overshoot: $\% \psi_{os}$ (percent)	22	28	1.27
Track Response Variables			
Max crosstrack excursion: D_{max} (feet)	533	589	1.11
Crosstrack overshoot: $\% D_{os}$ (percent)	330	367	1.11
TURNING CIRCLE MANEUVER (35 deg rudder)			
Tactical diameter (feet)	3625	3657	1.01
Advance (feet)	2114	2192	1.04
Transfer (feet)	1700	1811	1.07

TABLE 11. COMPARISON OF INHERENT CONTROLLABILITY FOR AN 80,000 DWT TANKER AT 6 AND 10 KNOTS; 1-FOOT UNDERKEEL CLEARANCE

20/20 Z MANEUVER	80,000 dwt	80,000 dwt	Ratio
Turn Response Variables	6 knots	10 knots	10/6
Rise time T_{20} (seconds)	150	92	0.61
Heading Lag: $T_{\psi lag}$ (seconds)	60	39	0.65
Displacement Lag: T_{Dlag} (seconds)	260	168	0.65
1/max slew rate: $1/\dot{\psi}_{max}$	5.6 sec/deg	3.3 sec/deg	0.59
Distance travel for: T_{20} (feet)	1476	1511	1.02
Distance travel for: $T_{\psi\ lag}$ (feet)	559	589	1.05
Distance travel for: T_{Dlag} (feet)	2356	2527	1.07
Distance travel for max heading change	52.6 ft/deg	52.6 ft/deg	1.00
Heading Response Variables			
Max heading excursion: ψ_{max} (degrees)	24.8	25.8	1.04
Heading overshoot: $\% \psi_{os}$ (percent)	24	29	1.21
Track Response Variables			
Max crosstrack excursion: D_{max} (feet)	810	865	1.07
Crosstrack overshoot: $\%D_{os}$ (percent)	459	492	1.07
TURNING CIRCLE MANEUVER(35 deg rudder)			
Tactical diameter (feet)	3753	3760	1.00
Advance (feet)	2496	2558	1.02
Transfer (feet)	1790	1958	1.09

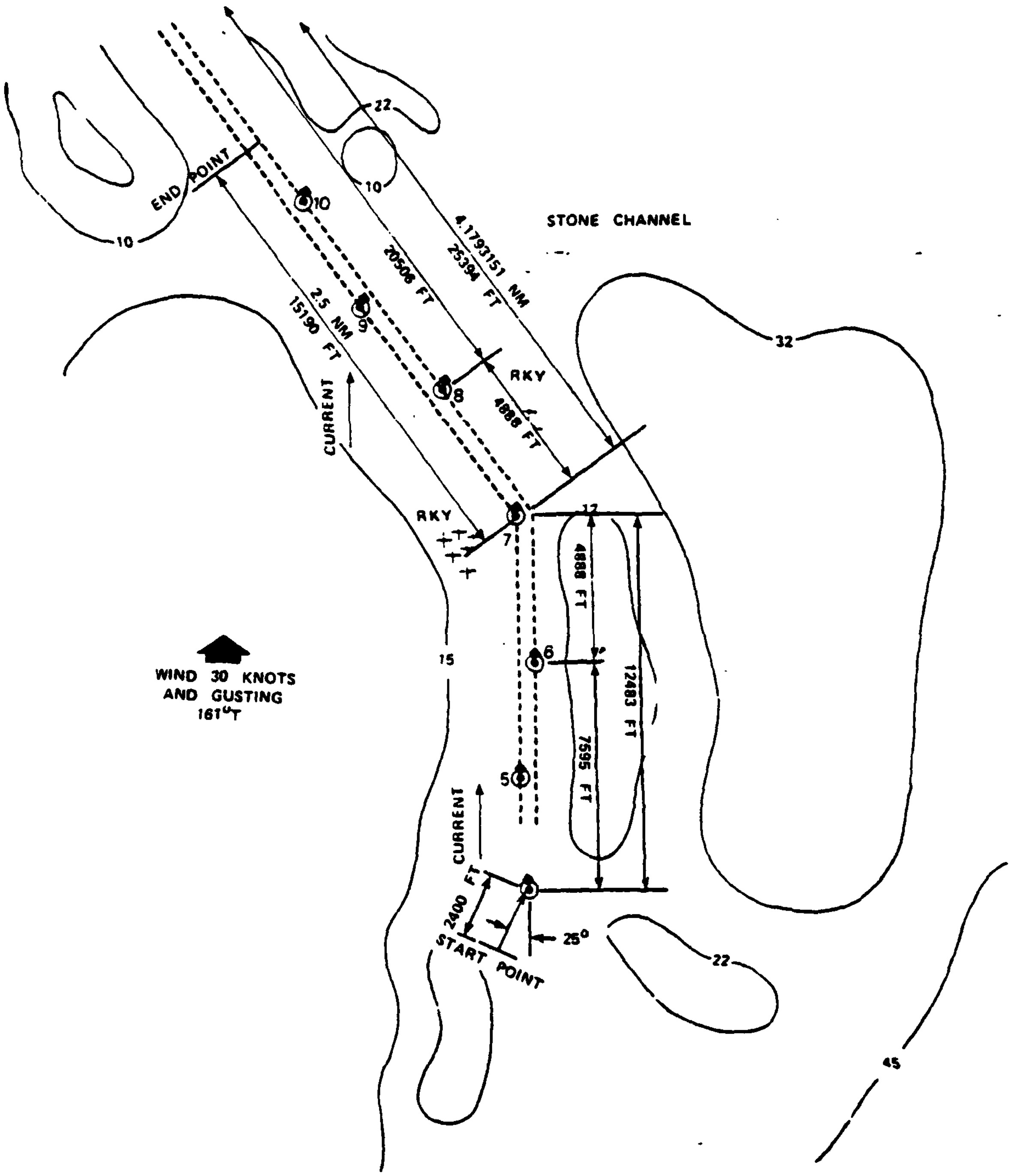


Figure 31. Chart 2 - Low Information Density

The data in Figure 32 show the performance of the 30,000 dwt tanker at both 6 and 10 knots. These combined plots indicate that, indeed, the pilots successfully navigated the low buoy density channel. Comparison plots of crosstrack mean and standard deviations are shown in Figure 33 for these conditions. The data are remarkably similar in Leg 1, the turn, and Leg 2. No data points are indicated to be statistically different at the 0.10 confidence level. The data in Region 4, nevertheless warrant further discussion. It is observable that the lateral set from right to left in Leg 2 (data lines 16 to 26) is reduced in magnitude by increased ship's speed. This reduction supports the previous hypothesis that this set is caused by the wind-induced turning moment and the resultant "walking" of the ship windward. At the higher ship speed the rudder is more effective in checking the wind-induced turning moment and the ship transits the leg much faster reducing the period during which the perturbation acts. The net effect appears to be a mean course at higher speed which more closely parallels the channel centerline. It is noteworthy that increased speed does not reduce the width of the perceived "center" of the channel since a 75 foot bias to the right of the centerline remains.

The reduced standard deviation in Region 4, while not statistically supported to be less, indicates a trend that higher speed may be of some aid in achieving more consistent trackkeeping performance in perturbing wind and current conditions. As this difference is not statistically supportable, the improvement is likely to be relatively small.

The data for the 80,000 dwt ship at 6 and 10 knots more or less parallels the findings for the 30,000 dwt but the findings are somewhat masked by the fact that the 80,000 dwt versus the 30,000 dwt is a more difficult ship to handle. (See previous section.) The data in Figure 34 show the combined plots for the two speeds. A problem in entering the channel and in completing the turn is emphasized by the location of portions of the combined plot lying beyond the channel edge. The comparison plots of the crosstrack mean and standard deviation in Figure 35 indicate the differences. Some improvement in performance is evident in Region 1 of Leg 1. The standard deviation for 10 knots is less than that for 6 knots. Here, the higher speed aids in recovering from the turn into the channel. The improvement, however, is very localized and may indicate differences in strategy and in initial course. Note that shifting the 10 knot standard deviation curve in Leg 1 to the right would cause the 6 and 10 knot curves to nearly coincide. Thus the improvement in Leg 1 appears to be less apparent.

The turning performance indicated in Region 2 shows a high crosstrack standard deviation exiting the turn at 6 knots. While not statistically different from that observed for 6 knots, the data indicate that turning at 10 knots may be somewhat less consistent than at 6 knots. This degradation, however, may be relatively small since the increase is not statistically supportable.

Trackkeeping performance in Region 4 shows that statistically significant differences occur in both the mean tracks and the standard deviations. The mean track for 10 knots indicates less lateral set similar to the 30,000 dwt tanker at 10 knots. Once again this is likely due to the ability to counter the wind perturbations with smaller rudder angles and the reduced time the ship requires to transit Leg 2 and experience the perturbations of wind and current.

The differences in crosstrack standard deviations in Leg 2 appear to occur as a result of oscillator behaviors which are out of phase. Comparison of the maximum

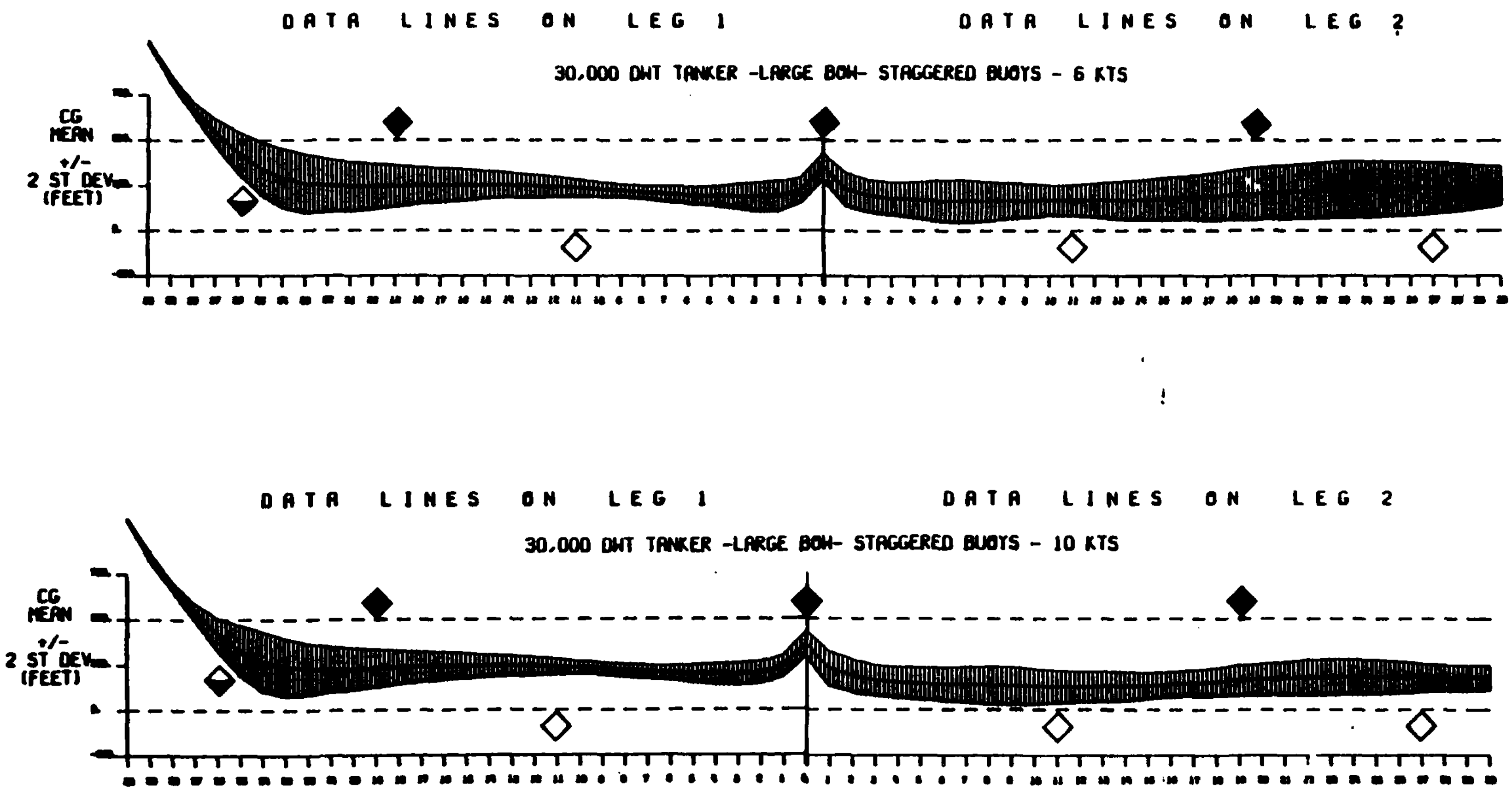


Figure 32. Combined Plot of Piloting Performance 30,000 DWT Tanker at 6 KTS and 10 KTS, Low Buoy Density

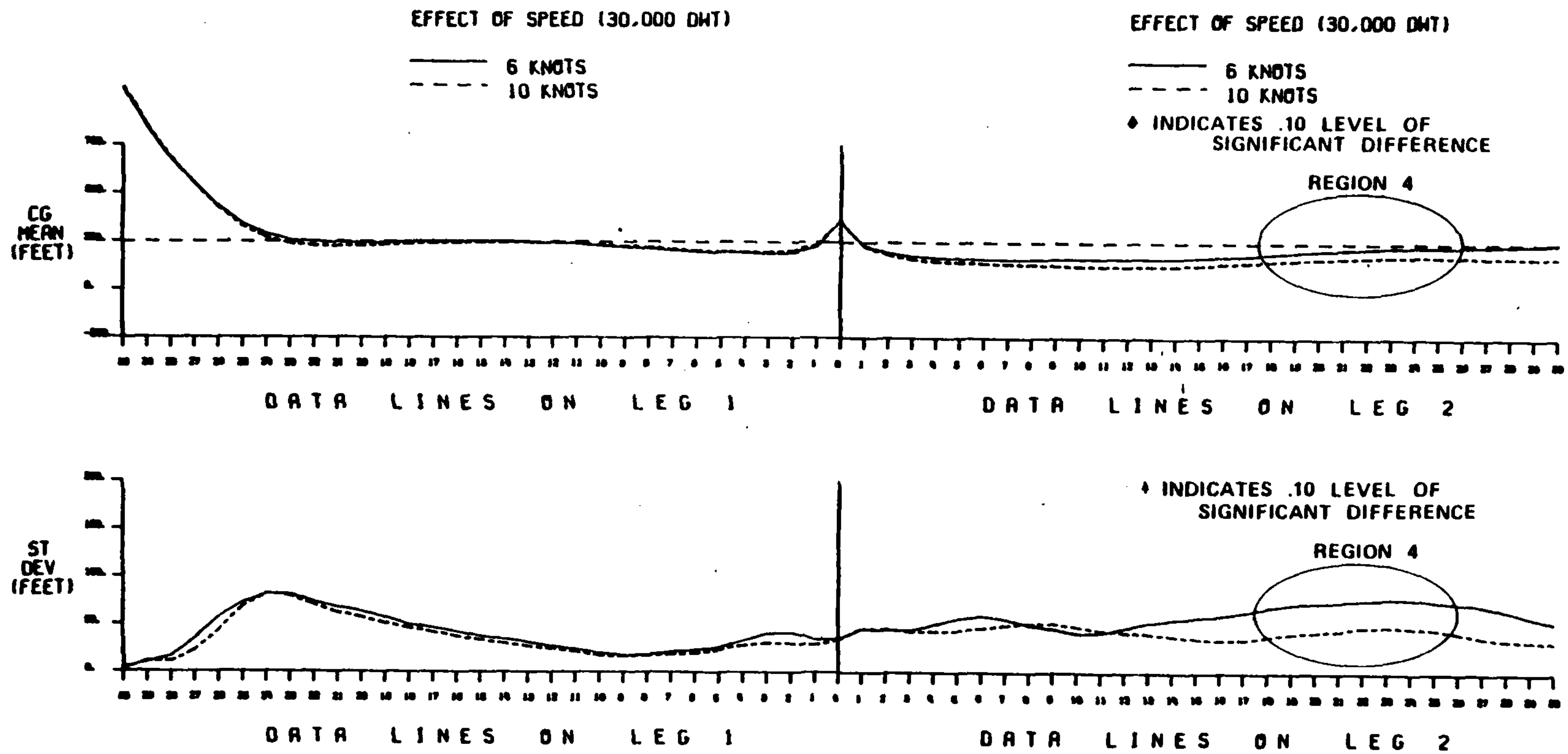


Figure 33. Crosstrack Mean and Standard Deviation of the Piloting Performance of a 30,000 dwt Tanker at 6 and 10 Kts, Low Buoy Density

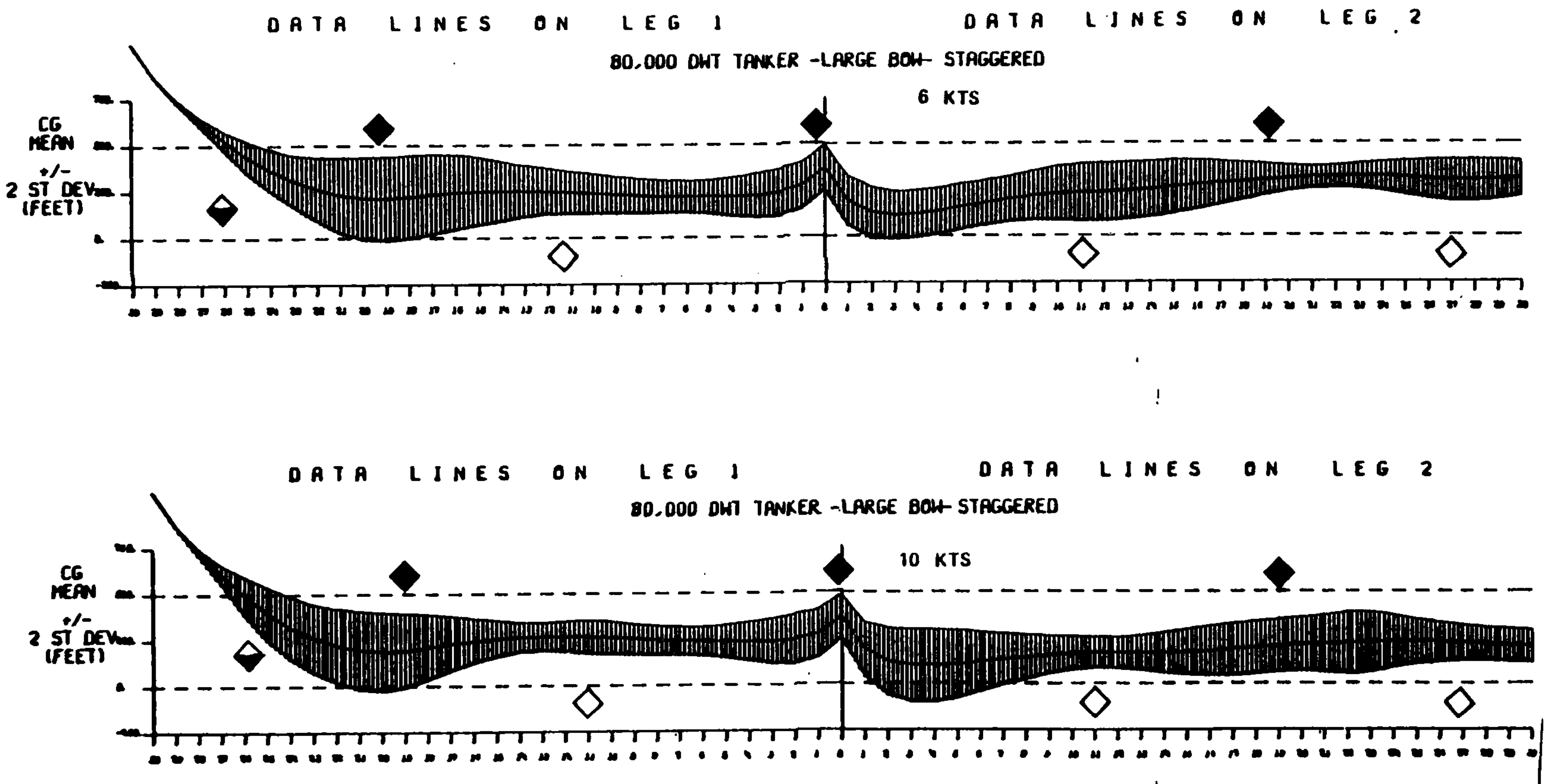


Figure 34. Combined Plots for the PilotingPerformance of an 80,000 dwt Tanker at 6 and 10 Kts, Low Buoy Density

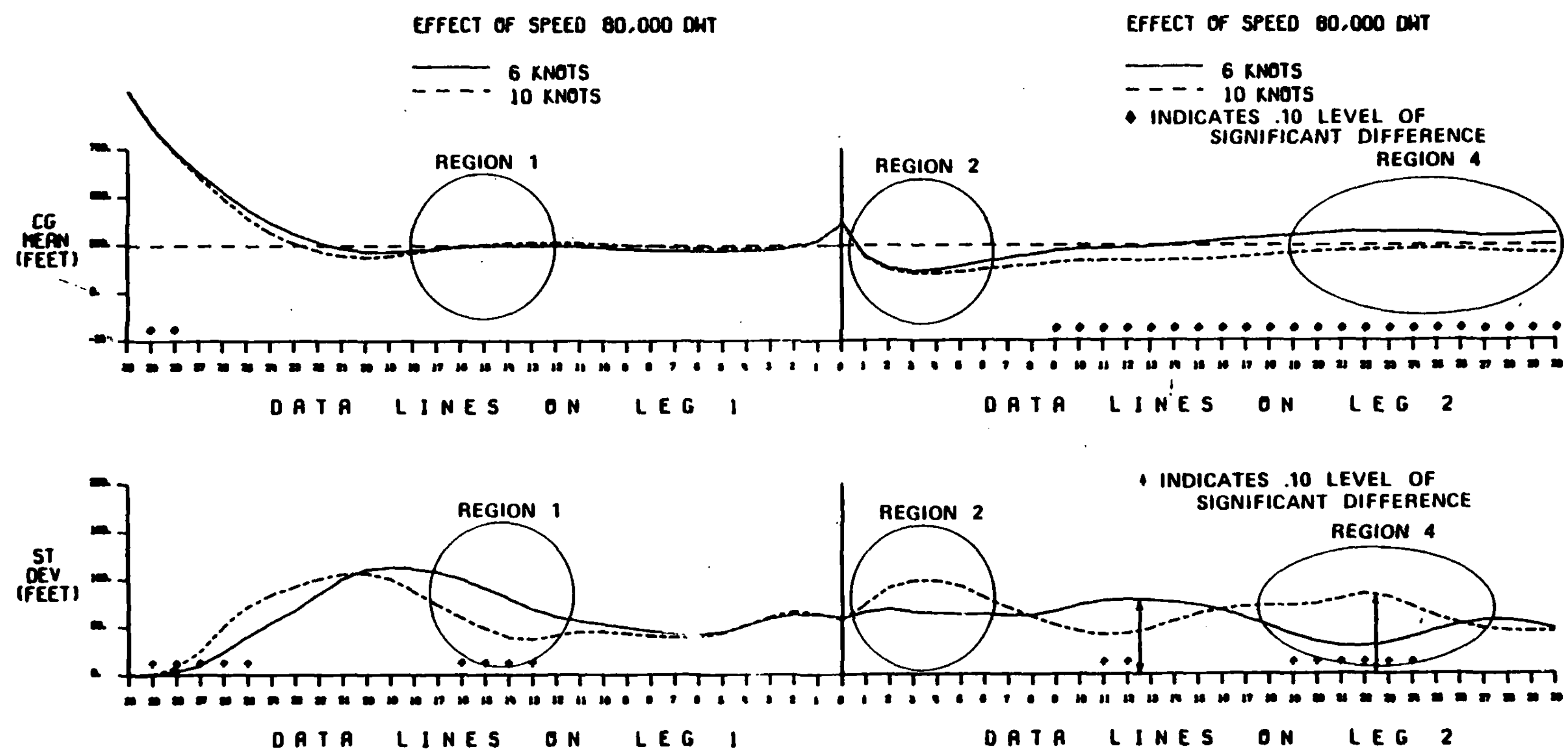


Figure 35. Crosstrack Mean and Standard Deviation for the Piloting Performance of an 80,000 dwt Tanker at 6 and 10 Kts, Low Buoy Density

standard deviations shows a slight increase in track variation at higher speed. Likely, such differences would not test to be statistically different. The source of the oscillatory behavior is unknown at this time. Its shift in phase can be attributed to overshooting the turn more at 10 knots and being forced to pass the first buoy close abeam. (see Figure 34). The period of the oscillatory behavior in distance is approximately 8500 feet or 1.4 nm. Since the buoy spacing is 1.25 nm it may be hypothesized that the oscillations occur as a function of buoy hopping or zig-zag in a staggered channel. Such behavior has been previously noted in staggered buoy configuration in the Channel Width experiment.

Considering the performance of both vessels, the expected improvement in maneuvering did not occur as a result of higher speed. Higher speed and larger more difficult to handle ships may actually degrade performance. The single instance in which speed may aid in piloting is trackkeeping in crosscurrents and in high winds. Unfortunately, few harbors require only trackkeeping skills. Thus, higher speed to compenstate for perturbing conditions must be weighed against possible degradation of turning performance. For large ships operating in narrow channels, the choice for low speed with high buoy density may be the most appropriate.

To the extent that the 35 percent improvement in turn response times did not significantly aid piloting, an interesting feature of the piloting process has been revealed: *the piloting process is not highly dependent on time-related decisions.* Evidently the pilot's perception and decision process is highly dependent on the distance domain visual cues and the distance response variables of the ship. This finding supports an important generalization regarding placement of aids to navigation.

1. Aids to navigation should be configured so as to provide an adequate and frequent indication of crosstrack position in trackkeeping portions of a channel.

2. Aids to navigation should be configured so as to provide an adequate and timely indication of both crosstrack and alongrack positions in the turning or maneuvering portions of a channel.

5.4 ANALYSIS OF THE EFFECT OF THE TURNING RESPONSE VARIABLE

The results of the speed comparison suggested that the 20/20 Z maneuver turn response variables in the time domain have little impact on piloting performance. A further test of this finding is available through the comparison of the 30,000 dwt and 80,000 dwt with identical time domain turn responses but track differences similar to those previously discussed in section 5.2. A comparison of the 30,000 dwt at 6 knots and the 80,000 dwt at 10 knots achieved the desired comparison The results of this comparison should be nearly equivalent to those of section 5.2 when both ships were tested at 6 knots.

The similarities in the turn response variables in the time domain are shown in Table 13 for the selected conditions. Yet, while these values are similar, the turn response variables and the track response variables are significantly different. Table 14 lists the average differences in response variable for both the 20/20 Z maneuver and the turning circle maneuver. As indicated, the turn response (distance domain) and the track response are 56 to 60 percent greater for the 80,000 dwt vessel. All other variables are relatively the same as indicated by modest increases in magnitude of 0 to 19 percent. It is instructive to compare Table 14 with Table 8 to verify that in the previous ship size comparison, the turn response time was also 60 percent higher.

TABLE 13. COMPARISON OF INHERENT CONTROLLABILITY FOR A 30,000 DWT VESSEL AT 6 KNOTS VERSUS AN 80,000 DWT VESSEL AT 10 KNOTS; 1-FOOT UNDERKEEL CLEARANCE

20/20 Z MANEUVER	30,000 dwt	80,000 dwt	Ratio
Turn Response Variables	6 knots	10 knots	80/30
Rise time: T_{20} (seconds)	110	92	0.83
Heading Lag: $T_{\psi lag}$ (seconds)	30	39	1.30
Displacement Lag: T_{Dlag} (seconds)	160	168	1.05
1/max slew rate: $1/\dot{\psi}_{max}$	4 sec/deg	3.3 sec/deg	0.83
Distance Travel For: T_{20} (feet)	1097	1511	1.38
Distance Travel For: $T_{\psi lag}$ (feet)	292	589	2.02
Distance Travel For: T_{Dlag} (feet)	1546	2527	1.63
Distance Travel For Max Heading Change	38.5 ft/deg	52.6 ft/deg	1.37
Heading Response Variables			
Max Heading Excursion: ψ_{max} (degrees)	24.4	25.8	1.06
Heading overshoot: % ψ_{os} (percent)	22	29	1.32
Max Crosstrack Excursion: D_{max} (feet)	533	865	1.62
Crosstrack Overshoot: % D_{os}	330	492	1.49
TURNING CIRCLE MANEUVER (35 deg rudder)			
Tactical diameter (feet)	3625	3760	1.04
Advance (feet)	2114	2558	1.21
Transfer (feet)	1700	1958	1.15

TABLE 14. AVERAGE CHANGES OF INHERENT CONTROLLABILITY FOR AN 80,000 DWT TANKER AT 10 KNOTS VERSUS A 30,000 DWT TANKER AT 6 KNOTS, 1-FOOT UNDERKEEL DEPTH

20/20 Z MANEUVER	% Increase
Turn Response (Time Domain)	0
Turn Response (Distance Domain)	60
Heading Response	19
Track Response	56
TURNING CIRCLE MANEUVER	
Average Response Change	13

Performance under these two conditions is shown in the combined plots in Figure 36. The aids to navigation conditions are identical to those used for the speed comparison, low density. (see Figure 31). Comparisons of the crosstrack means and standard deviations are shown in Figure 37. Highlighted are the regions of significant performance differences.

Significant differences in standard deviations occur in Leg 1. These data show the standard deviation increases from 22 feet to 45 feet, an increase of 104 percent for the 80,000 dwt vessel. Similar differences in standard deviation occur in Region 2 where the standard deviation increases from 45 feet to 97 feet, an increase of 115 percent.

The data in Figure 37 also indicate a statistically significant difference in mean tracks following the turn in Region 2. This difference verifies the track overshoot previously indicated for the 80,000 dwt vessel. Table 15 summarized the performance differences. Comparison of Table 15 to Table 9 reveals that these numbers are nearly equivalent in magnitude and difference to values found at conclusion that only differences in 20/20 Z maneuver track response and turn response in the distance domain result in meaningful performance differences. These data further verify that:

The percent increase in crosstrack standard deviation between ships is approximately 1-1/2 times the average percent increases in the turn response (as measured in the distance domain) and track response variables of the 20/20 Z maneuvers.

5.5 ANALYSIS OF THE EFFECT OF UNDERKEEL CLEARANCE

The foregoing analyses permit an extrapolation of findings to the variable of underkeel clearance. If it is valid to utilize parameters of the 20/20 Z maneuver to predict differences between ships, then a similar process might be used to estimate the effects of changes in one ship's inherent controllability caused by changes in underkeel depth. All simulations discussed to this point were conducted with 1-foot

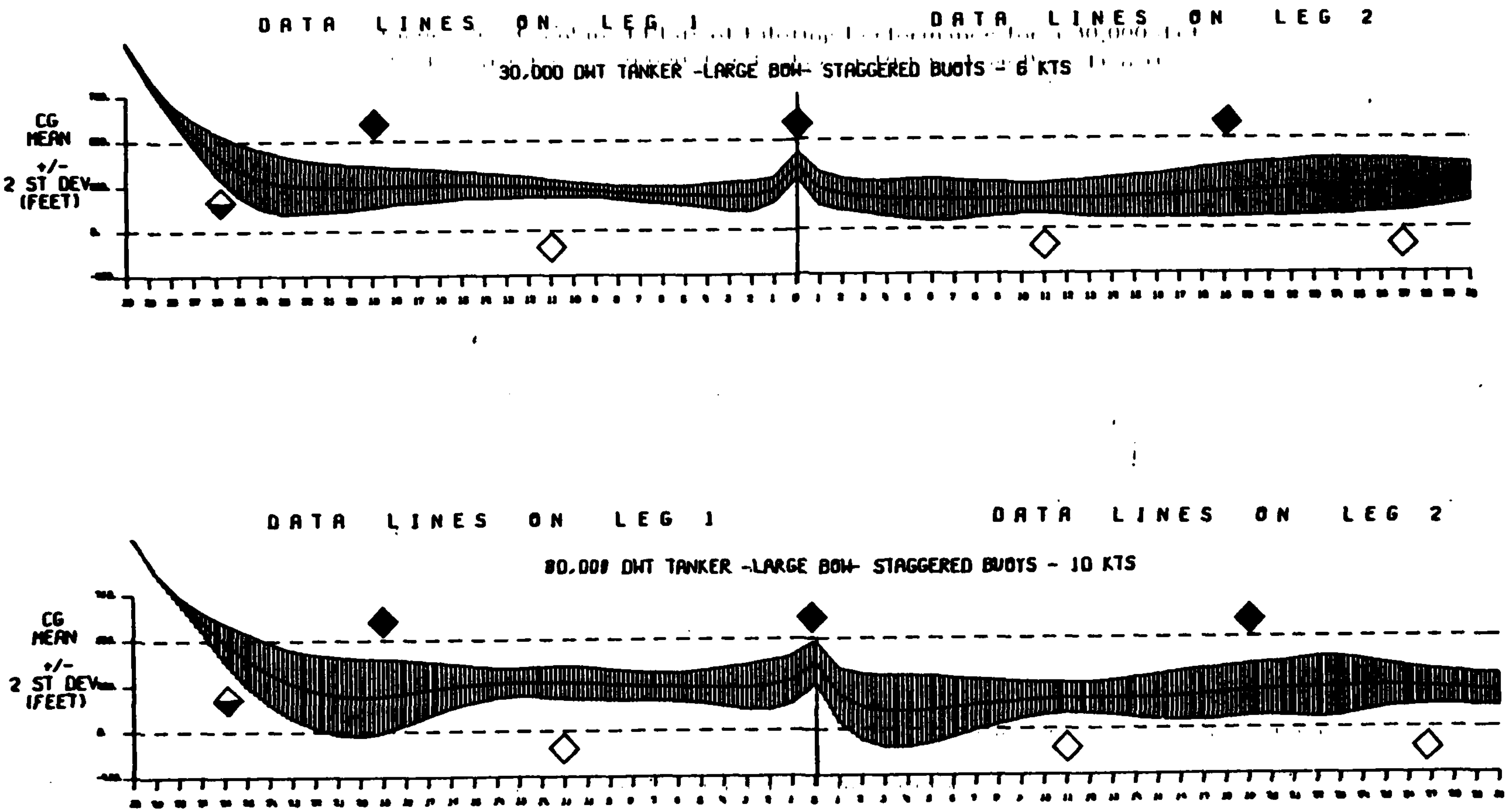


Figure 36. Combined Plots of Piloting Performance for a 30,000 dwt Tanker at 6 Kts vs 80,000 dwt Tanker at 10 Kts, Low Buoy Density

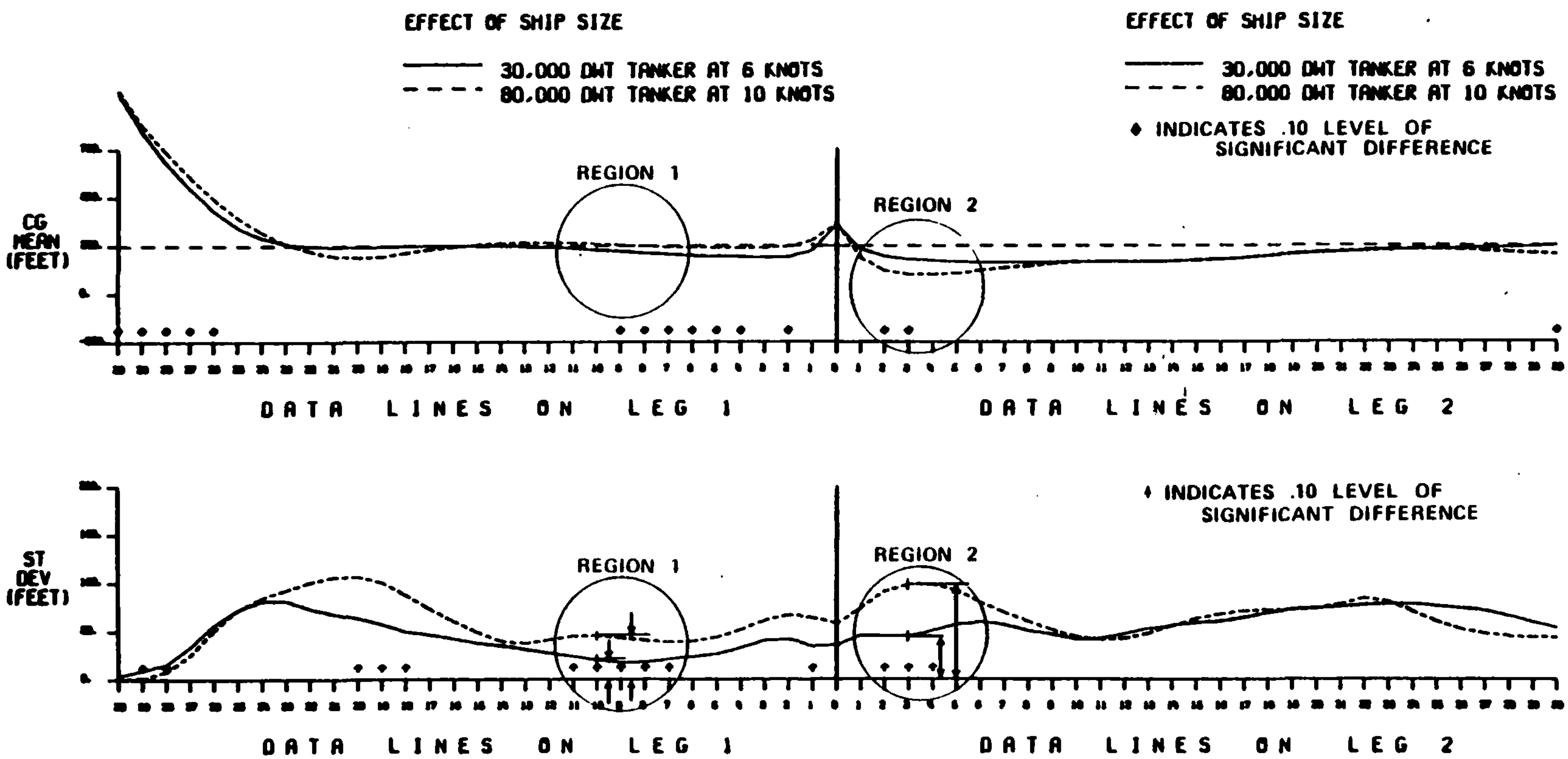


Figure 37. Crosstrack Mean and Standard Deviation of Piloting Performance for a 30,000 dwt Tanker at 6 Kts vs 80,000 at 10 Kts, Low Buoy Density

TABLE 15. CROSSTRACK PERFORMANCE DATA, 30,000 DWT AT 6 KNOTS VERSUS 80,000 DWT AT 10 KNOTS

	MEAN CROSSTRACK POSITION	
	30,000 dwt 6 knots	80,000 dwt 10 knots
Region 1 (feet)	SAME	
Region 2 (feet)	72	151

	CROSSTRACK STANDARD DEVIATION		
	30,000 dwt 6 knots	80,000 dwt 10 knots	80 vs 30 % Increase
Region 1 (feet)	22	45	104
Region 2 (feet)	45	97	115

simulated underkeel clearance. Computer simulations of 20/20 Z maneuvers in deep water (600 feet) were subsequently run to determine differences in inherent controllability. Tables 16 and 17 summarize the results for the 30,000 dwt and 80,000 dwt vessels respectively. All runs were conducted at 6 knots.

The data derived indicate relatively small differences occurred except in the overshoot values for the Z maneuver and the changes in turning circle variables. The average changes in the groups of variables are listed in Table 18. These values indicate that for deep water, the ships exhibit more overshoot (increased heading response and track response) and smaller turning circle values (decreases in average response changes). The exact impact of these data is difficult to predict other than as trends. It may be hypothesized that:

1. For piloting in narrow channels with turn angles equal to or less than 35 degrees, a small underkeel clearance is beneficial in reducing crosstrack standard deviations.

2. For transiting large angle turns (angle exceeding 35 degrees), a small underkeel clearance is detrimental to achieving the desired mean track.

Further experimental testing with large underkeel clearance would provide an isolated look at the effects of heading and distance overshoot alone on piloting performance. Such tests need to be conducted to more accurately predict changes in piloting performance as a function of changes in inherent controllability.

TABLE 16. COMPARISON OF INHERENT CONTROLLABILITY FOR A 30,000 DWT TANKER FOR VARIOUS UNDERKEEL CLEARANCES, 6 KNOTS

20/20 Z MANEUVER	30,000 dwt		Ratio
Turn Response Variables	1-ft underkeel	600-ft underkeel	600/1ft
Rise Time: T_{20} (seconds)	100	93	0.85
Heading Lag: T_{lag} (seconds)	30	40	1.33
Displacement Lag: T_{Dlag} (seconds)	160	160	1.00
1/max slew rate: 1/max	4 sec/deg	3.2 sec/deg	0.80
Distance Travel For: T_{20} (feet)	1097	950	0.87
Distance Travel For: T_{lag} (feet)	292	406	1.39
Distance Travel For: T_{Dlag} (feet)	1546	1646	1.06
Distance Travel For Max Heading Change	38.4 ft/deg	33.3 ft/deg	0.87
Heading Response Variable			
Max Heading Excursion: ψ_{max} (degrees)	24.4	25.9	1.06
Heading Overshoot: % ψ_{os}	22	30	1.36
Max Crosstrack Excursion: D_{max} (feet)	533	523	0.98
Crosstrack Overshoot: % D_{os}	330	545	1.65
TURNING CIRCLE MANEUVER (35 deg rudder)			
Tactical diameter (feet)	3625	2517	0.69
Advance (feet)	2114	1811	0.86
Transfer (feet)	1700	1174	0.69

TABLE 17. COMPARISON OF INHERENT CONTROLLABILITY FOR AN 80,000 DWT TANKER FOR VARIOUS UNDERKEEL CLEARANCES, 6 KNOTS.

20/20 Z MANEUVER	80,000 dwt		Ratio
Turn Response Variables	1-ft underkeel	600-ft underkeel	600/1ft
Rise Time: T_{20} (seconds)	150	125	0.83
Heading Lag: $T_{\psi lag}$ (seconds)	60	75	1.25
Displacement Lag: T_{Dlag} (seconds)	260	300	1.15
1/max slew rate: $1/\dot{\psi}_{max}$	5.6 sec/deg	4.0 sec/deg	0.71
Distance Travel For: T_{20} (feet)	1476	1253	0.85
Distance Travel For: $T_{\psi lag}$ (feet)	559	708	1.27
Distance Travel For: T_{Dlag} (feet)	2356	2784	1.18
Distance Travel For Max Heading Change	52.6 ft/deg	38.9 ft/deg	0.74
Heading Response Variables			
Max Heading Excursion: ψ_{max}(degrees)	24.8	28.7	0.16
Heading Overshoot: % ψ_{os}	24	44	1.83
Max Crosstrack Excursion: D_{max} (feet)	810	940	1.16
Crosstrack Overshoot: %D_{os}	459	1100	2.40
TURNING CIRCLE MANEUVER (35 deg rudder)			
Tactical Diameter (feet)	3753	2423	0.64
Advance (feet)	2496	1988	0.80
Transfer (feet)	1790	946	0.53

TABLE 18. AVERAGE CHANGES IN INHERENT CONTROLLABILITY FOR CHANGES IN UNDERKEEL CLEARANCE FROM 1-FOOT TO 600 FEET

20/20 Z MANEUVER	30,000 dwt	80,000 dwt
	% Change	
Turn Response (Time Domain)	0	2 (decrease)
Turn Response (Distance Domain)	5 (increase)	1 (increase)
Heading Response	21 (increase)	50 (increase)
Track Response	31 (increase)	78 (increase)
TURNING CIRCLE MANEUVER		
Average Response Change	25 (decrease)	34 (decrease)

APPENDIX A

IDENTIFICATION OF SHIP VARIABLES

A.1 INTRODUCTION

Comparisons of the ships and conditions of the experiment provide some insight with regard to performance differences observed between the various experimental conditions. This appendix addresses the physical differences and also the differences in inherent controllability[1] between the ship simulations used in the experiment.

A.2 PHYSICAL CHARACTERISTICS OF THE VESSELS

Three different vessels were utilized in the experiment. They differed in size, wheelhouse location, bridge wing configuration, bow image, and height of eye for the pilot. Table A-1 lists the conditions for these vessels in the eight scenarios.

The two 30,000 dwt ships indicated are identical in inherent controllability but differ in *bow image* and *bridge wings*. The ship with the small bow image and no bridge wings is a special experimental case which is utilized to test an hypothesis regarding visual cues utilized in piloting. It does not represent an actual ship. The other 30,000 dwt and the 80,000 dwt ship represent actual hull configurations.

The 30,000 dwt and 80,000 dwt ships differ in physical dimensions according to the data listed in Table A.2. Figures A.1 and A.2 show the ships' dimensions and the eye point location. A vertical line through the ship's center of gravity is shown as a reference for the eye point. This point is to be distinguished from the ship's actual rotation point which varies in location during maneuvers and is typically located approximately 1/3 the ship's length back from the bow.

The plans and sections of the wheelhouse and bridge wing configurations are shown in Figures A.3 and A.4. Figure A.3 shows the configuration for the small-bow/no-bridge-wing condition. This condition is typical of a tug/push-boat configuration. Figure A.4 shows the configurations for typical merchant ships with the exception that the wheelhouse is exceptionally narrow. This configuration was assumed for the other 30,000 dwt ship and the 80,000 dwt ship with the differences in dimensions noted. This design is believed to be acceptable for experimentation since most visual elements are as if the piloting position is on the ship's longitudinal centerline. This position is the principal piloting position for most restricted waterway operations.[2] The addition of bridge wings and the open railing forward of the bridge provided realistic masking of the visual scene abeam of ownship. The bridge wings and railing provide "visual anchors" for buoys passing abeam thus aiding the process of perceiving crosstrack velocity as the ship passes successive buoys.

[1] Society of Naval Architects and Marine Engineers, Panel H-10 (Ship Controllability). "Proposed Procedures for Determining Ship Controllability Requirements." STAR Symposia, August 1975

[2] A. J. Pesch and W. R. Bertsche. "Volume I - Executive Summary: An Automated Standardized Bridge Design for the U. S. Merchant Marine." Office of Commercial Development, U. S. Maritime Administration, Washington, D. C., September, 1976.

TABLE A-1. SHIP PHYSICAL CHARACTERISTICS BY SCENARIO

SCENARIO	SHIP SIZE (DWT)	SHIP TYPE	WHEELHOUSE LOCATION	HEIGHT OF EYE (FEET)	BOW IMAGE	BRIDGE WINGS
1	30,000	Tanker	Midship	45	Small	No
2,3,5	30,000	Tanker	Midship	45	Normal	Yes
6,7,8	80,000	Tanker	Aft	80	Normal	Yes

TABLE A.2. COMPARISON OF SHIP DIMENSIONS
30,000 DWT VERSUS 80,000 DWT TANKERS

	30,000	80,000
LENGTH (FEET)	596	763
BEAM (FEET)	84	125
DISPLACEMENT (TONS)	39,000	100,000

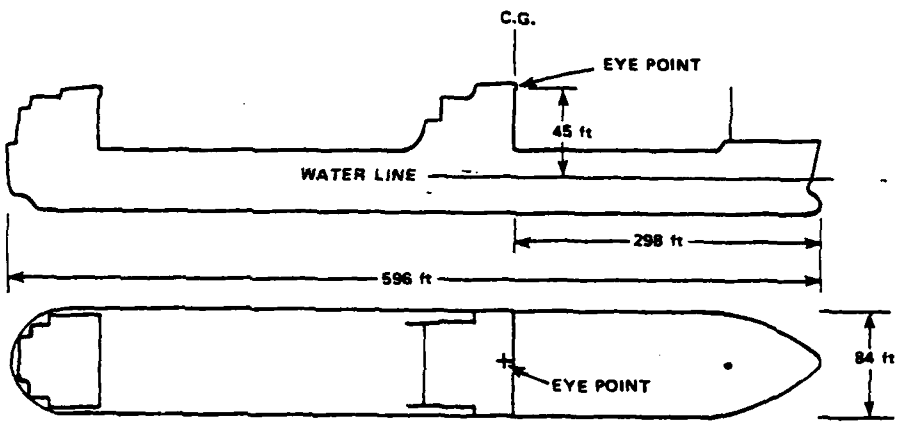


Figure A.1. Plan and Evaluation of a 30,000 dwt Tanker

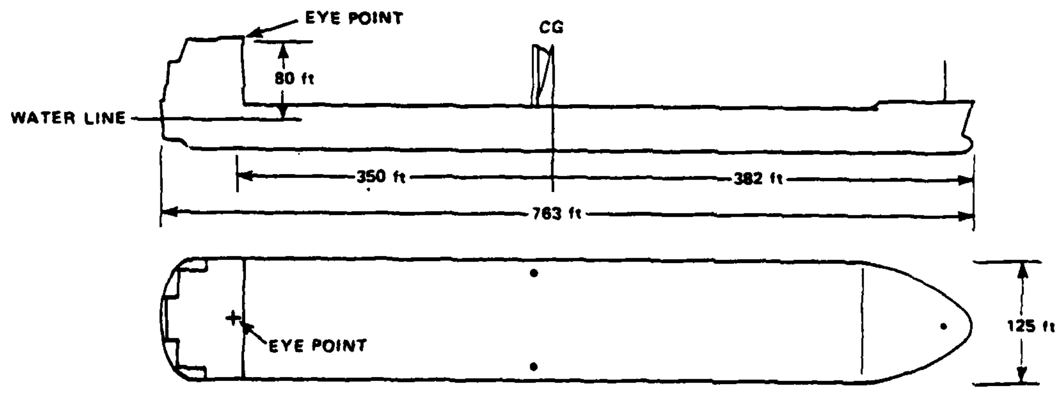
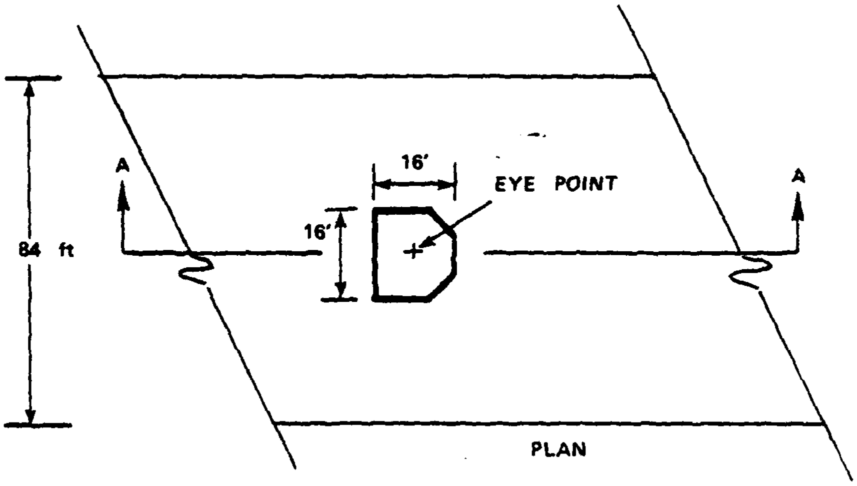
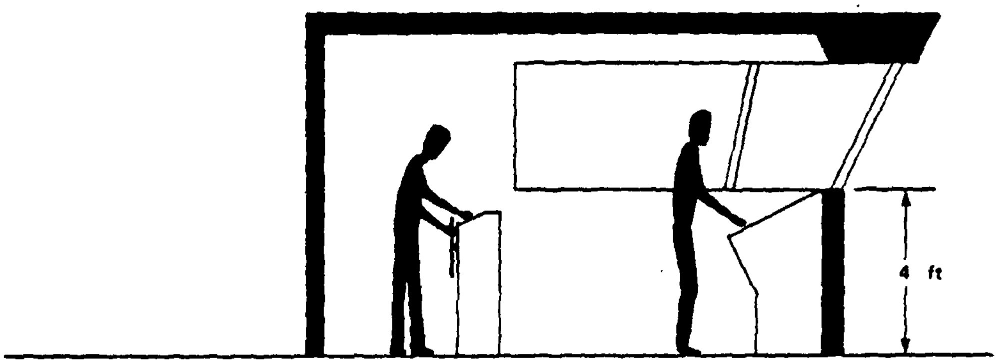


Figure A.2. Plan and Evaluation of an 80,000 dwt Tanker

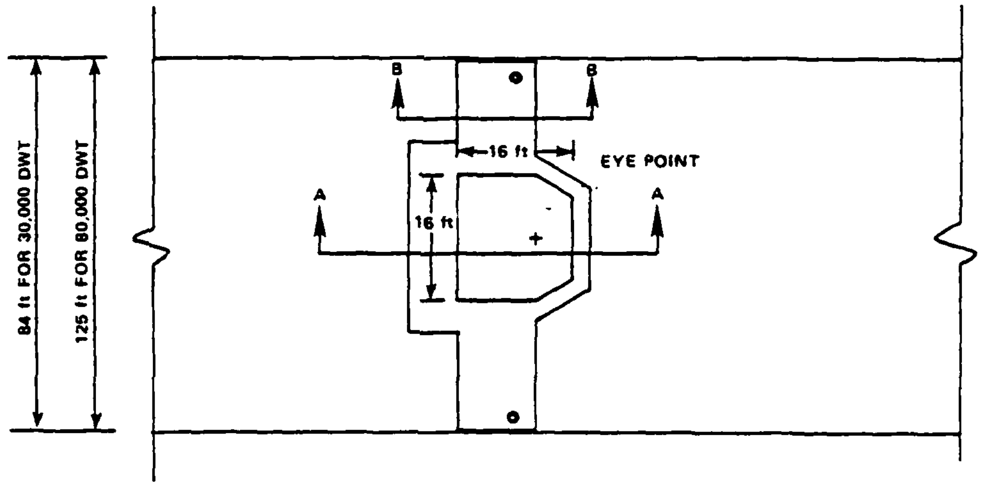


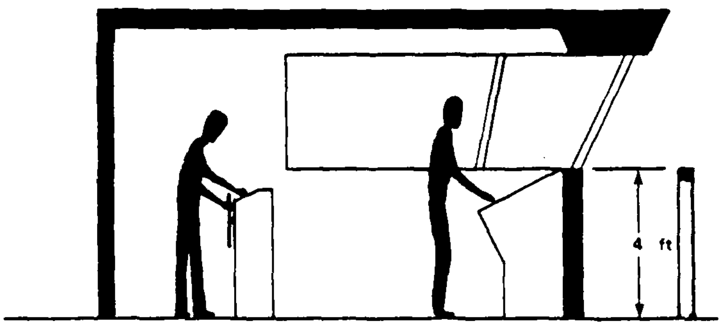
PLAN



SECTION AA

Figure A.3. Plan and Section of Wheelhouse without Br:dge Wings on 30,000 dwt Tanker





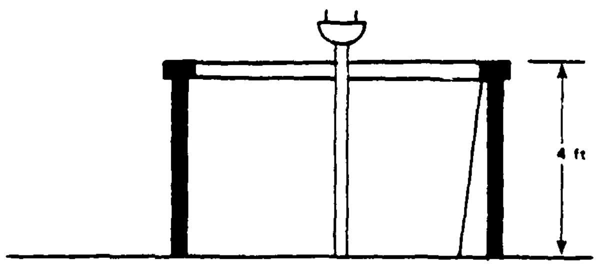


Figure A.4. Plan and Sections for Wheelhouse with Bridge Wings on 30,000 dwt and 80,000 dwt Tanker

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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT ON THE SHIP VARIAB--ETC(U)
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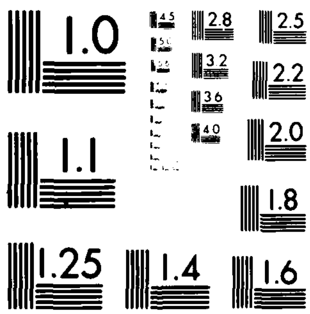


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

The difference in eye height (45 feet versus 80 feet) results in a change in the slope of the path of the buoys relative to the horizon. Figure A.5 shows the visual paths of the buoys for the two heights of eye. The angle of the path is 10 degrees* down from the horizon for the 30,000 dwt tanker and 18 degrees* down from the horizon for the 80,000 dwt tanker.

*NOTE: The angle assumes the ship is traveling on the centerline of a 500-foot wide channel:

$$\text{Angle} = \tan^{-1} (\text{height of eye/half the channel width})$$

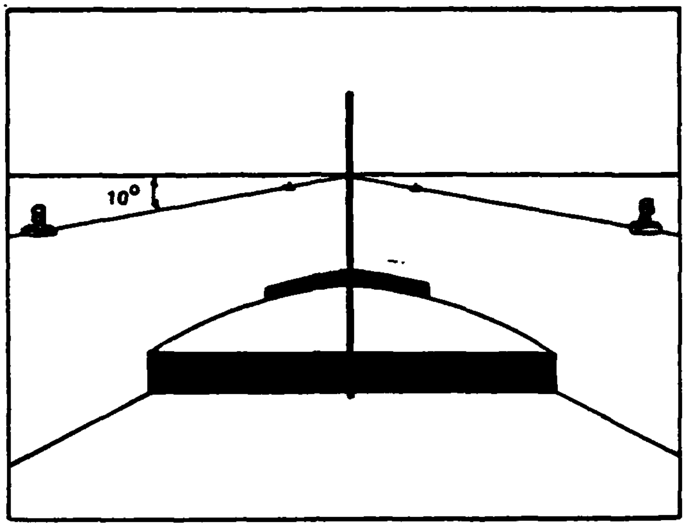
It had been hypothesized that a greater height of eye would improve piloting accuracy since for a greater height of eye changes in crosstrack position result in larger changes in the angle from the horizon. Figure A.6 shows a plot of the angle for various heights of eye and distances from the edge of the channel (D_e). The rate of change at the center of the channel is indicated for the two heights of eye. A more detailed analysis, however, shows that while for a 20-foot change in crosstrack distance the angular change for the 80-foot height of eye is greater, the proportional change is approximately the same for both eye heights. Table A.3 lists the angular values and proportional change for a 20-foot change in crosstrack position. A change of 1.5 degrees versus 0.9 degrees occurs for the greater height of eye but for both cases this represents approximately the same proportional (percent) increase in absolute angle.

The bow images utilized in the experiment were selected to be compatible with the selected eye point location and ship type. Figures A.7, A.8, and A.9 are diagrams of the three images utilized. Their silhouettes are shown together in Figure A.10 for comparison. A large and small bow image were tested on the 30,000 dwt tanker in order to identify the dependence of visual piloting on the visual image of the bow. It was hypothesized that more precise piloting performance would be possible when the edges of the bow image fall close to the paths of the buoys.

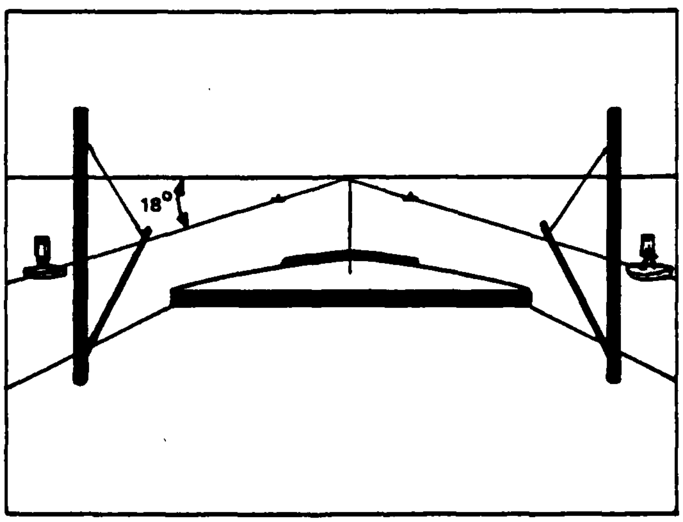
The midship versus aft wheelhouse locations were selected, first, to represent typical vessels and, second, to replicate conditions in all previous experiments. A 30,000 dwt tanker with midship wheelhouse was utilized in the CAORF Aids to Navigation experiment, Channel Width experiment, and the three Radio Aids to Navigation experiments.

Two differences occur when the eye point is shifted aft from the midship position. First, the motion and position of the entire vessel may be observed by the pilot during complex maneuvering problems (e.g., negotiating a turn, entering the channel). Given the entire picture, the pilot is perhaps somewhat more certain in initiating control orders, monitoring the results, and initiating corrective and/or refinement control orders. The position of aids close aboard may be monitored for the entire length of the ship until they pass abeam and, shortly afterwards, astern. The midship wheelhouse location allows a view of only the forward half of the vessel on the simulator. Aids may be monitored only during their passage along the forward half of the ship with a midship wheelhouse. The pilot must look astern to monitor aids close aboard the after half of the ship. The astern view is not available on the present simulator.

A second difference between wheelhouse locations occurs when pilots are forced to crab in a channel due to crosscurrents. The aft wheelhouse position requires the



45 FOOT HEIGHT OF EYE
30,000 DWT TANKER



80 FOOT HEIGHT OF EYE
80,000 DWT TANKER

Figure A.5. Comparison of Height of Eye Differences Between 30,000 dwt and an 80,000 dwt Tanker

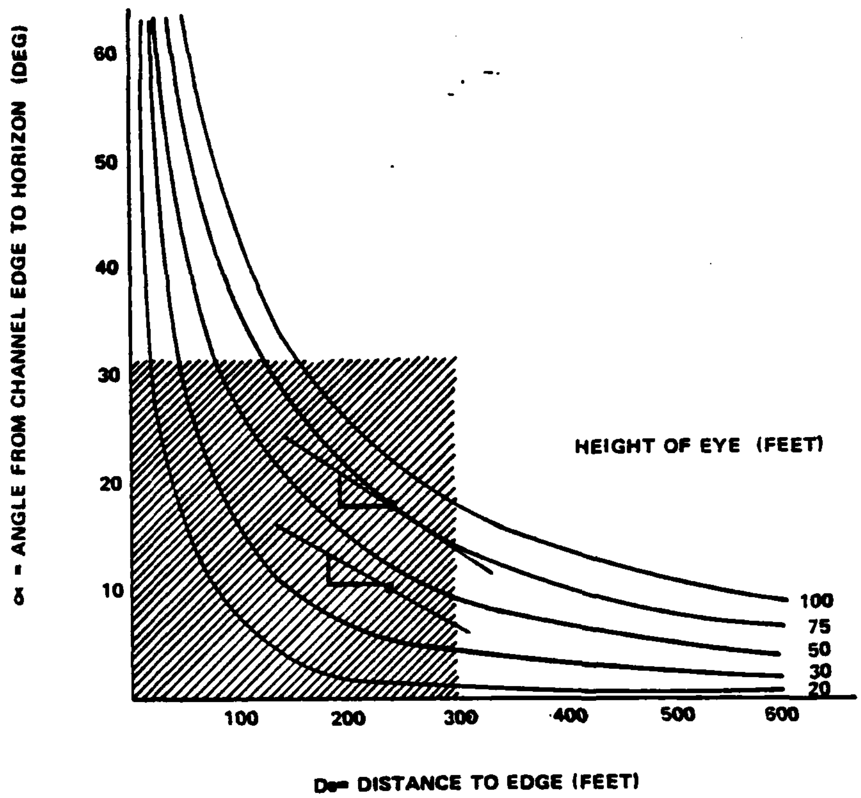


Figure A.6. Angle from Channel Edge to Horizon

TABLE A.3. CHANGES IN ANGLES OF BUOY PATH VERSUS HEIGHT OF EYE

HEIGHT OF EYE (feet)	45	80
ANGLE TO HORIZON AT CENTERLINE (degrees)	10.2	17.7
ANGLE TO HORIZON 20 FEET TO LEFT OF CENTERLINE (degrees)	11.1	19.2
CHANGE IN ANGLE (percent)	0.9	1.5
PROPORTIONAL CHANGE (percent)	8.8%	8.4%

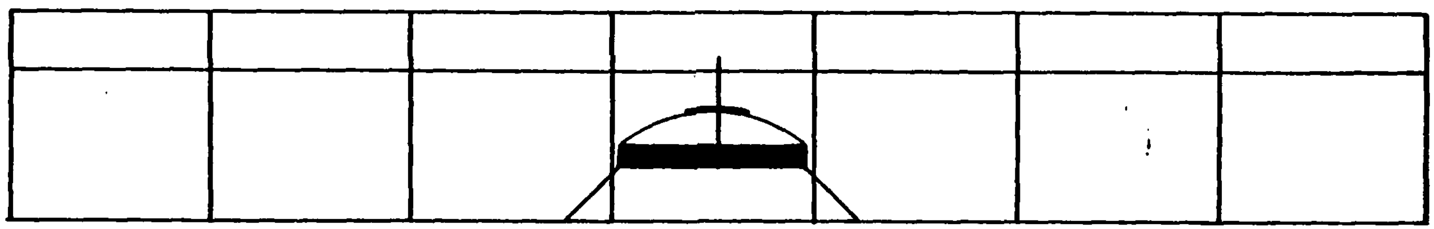


Figure A.7. Bow Image for a 30,000 dwt Tanker without Bridge Wings

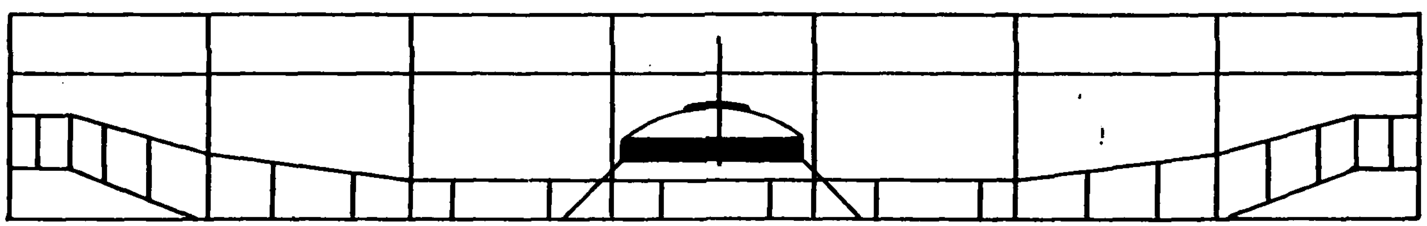


Figure A.8. Bow Image for a 30,000 dwt Tanker with Midship Wheelhouse

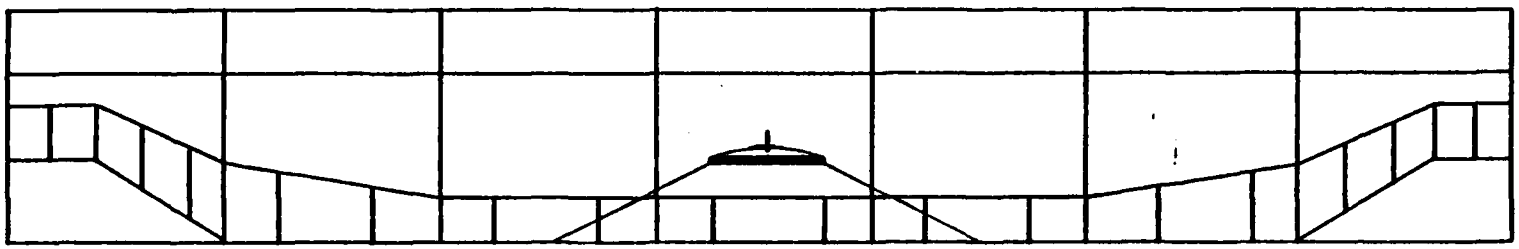


Figure A.9. Bow Image for an 80,000 dwt Tanker with Aft Wheelhouse

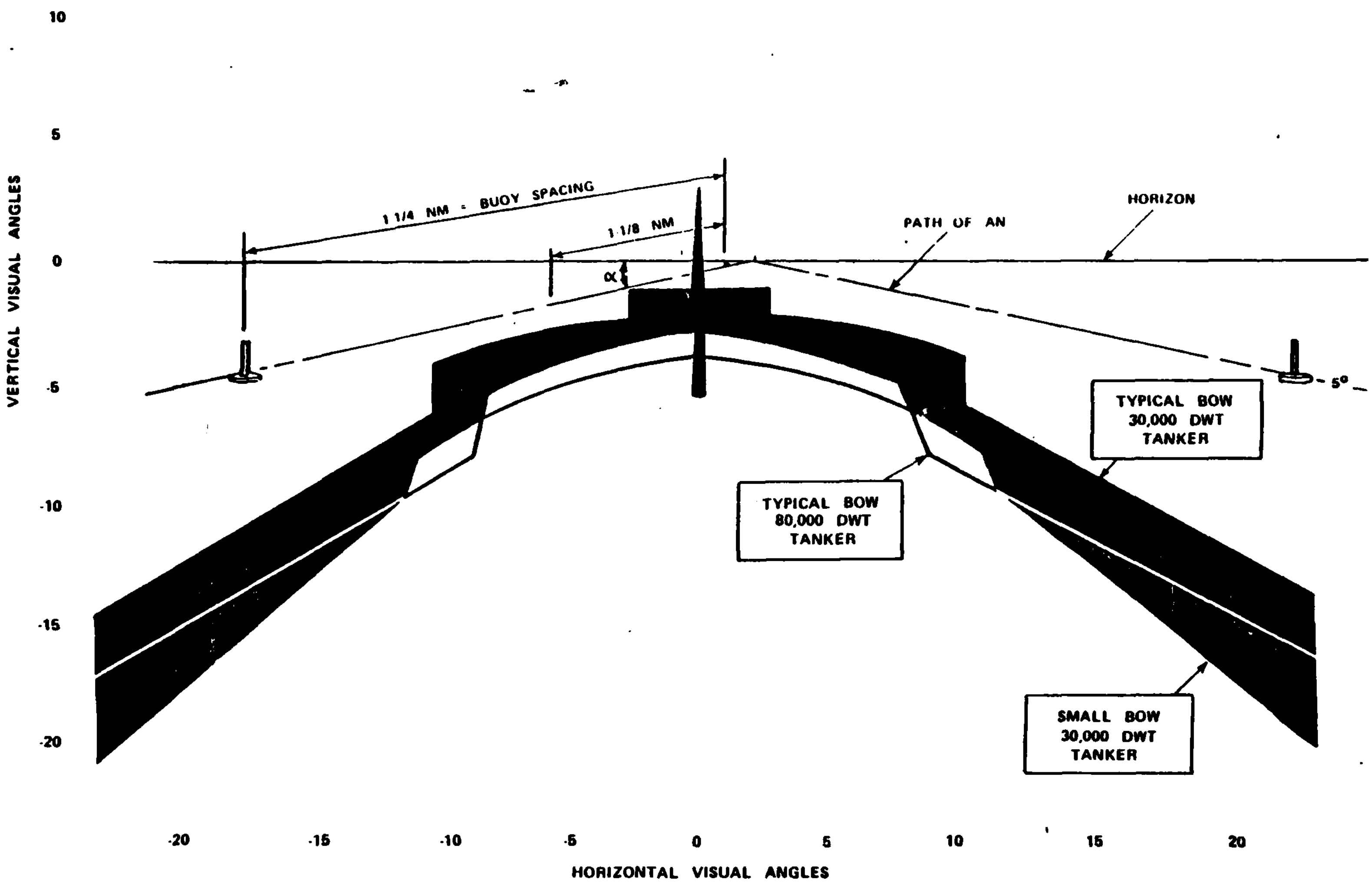


Figure A.10. The Silhouettes of the Bow Images used for Ship Variables Experiment

pilot to estimate the position of the ship's center of gravity from a position that is not on that center of gravity. When the wheelhouse is midships the pilot is located very near the ship's center of gravity. The differences in visual images of the buoys when crabbing is shown in Figure A.11 for the midship and aft wheelhouses. For the conditions where the center of gravity (CG) is on the centerline, the angles between the paths of the port and starboard buoys is the same for the midship wheelhouse ($\alpha = \beta$). For the aft wheelhouse, when the center of gravity is on the centerline, the eye point lies to the right of the centerline, resulting in different angles to the horizon ($\alpha < \beta$) and a slightly distorted visual image.

Overall, it has been hypothesized that the aft wheelhouse location is the preferred piloting position.

A.3 COMPARISON OF INHERENT CONTROLLABILITY FACTORS

In addition to the physical differences discussed in section A.2, the two ships differed in their hydrodynamic response to control actions. An analysis of this response was made in order to identify differences which are related to piloting differences observed experimentally. A study was made of the "inherent controllability" of the individual ships through the conduct and comparison of simulated sea trial maneuvers. In order to understand this approach, consider the diagram shown in Figure A.12. This is a simplified representation of a control loop where the ship is the vehicle to be controlled and the pilot serves as the controller. As indicated, the ship is identified to exhibit certain inherent controllability characteristics. The pilot's only input to the system is control orders. The ship and its systems respond to the orders via transfer functions as defined by the simulation hydrodynamic equations and coefficients. Comparison of these equations and coefficients, unfortunately, does not yield readily understandable differences between ships. We chose rather to determine response characteristics of the ship by providing a unique set of input control orders (driving functions) and observing the output response. The input functions, for our purposes, are a unique set of rudder commands which are typical of sea trial maneuvers.

Figure A.13 shows system configuration for these tests. Essentially, the ship is being studied "open loop" without the pilot. Various rudder commands (helm orders) are input and the ship's responses in terms of heading and track are recorded and analyzed. Two principal input maneuvers are studied, the turning circle and Z maneuver.

A.3.1 ANALYSIS OF TURNING CIRCLE MANEUVERS

The turning circle maneuver consists of commanding the rudder to a fixed position right or left from an initial condition of traveling in a straight line with the rudder amidships. The rudder is held in the fixed position until a 180-degree heading change occurs. The response parameters of interest are the following:

Tactical Diameter. Diameter of the turning circle between maneuver initiation and achievement of a 180-degree heading change.

Advance. Distance the ship advances between maneuver initiation and achievement of a 90-degree heading change.

Transfer. The lateral distance of the ship from the initial path of the ship when a 90-degree heading change is achieved.

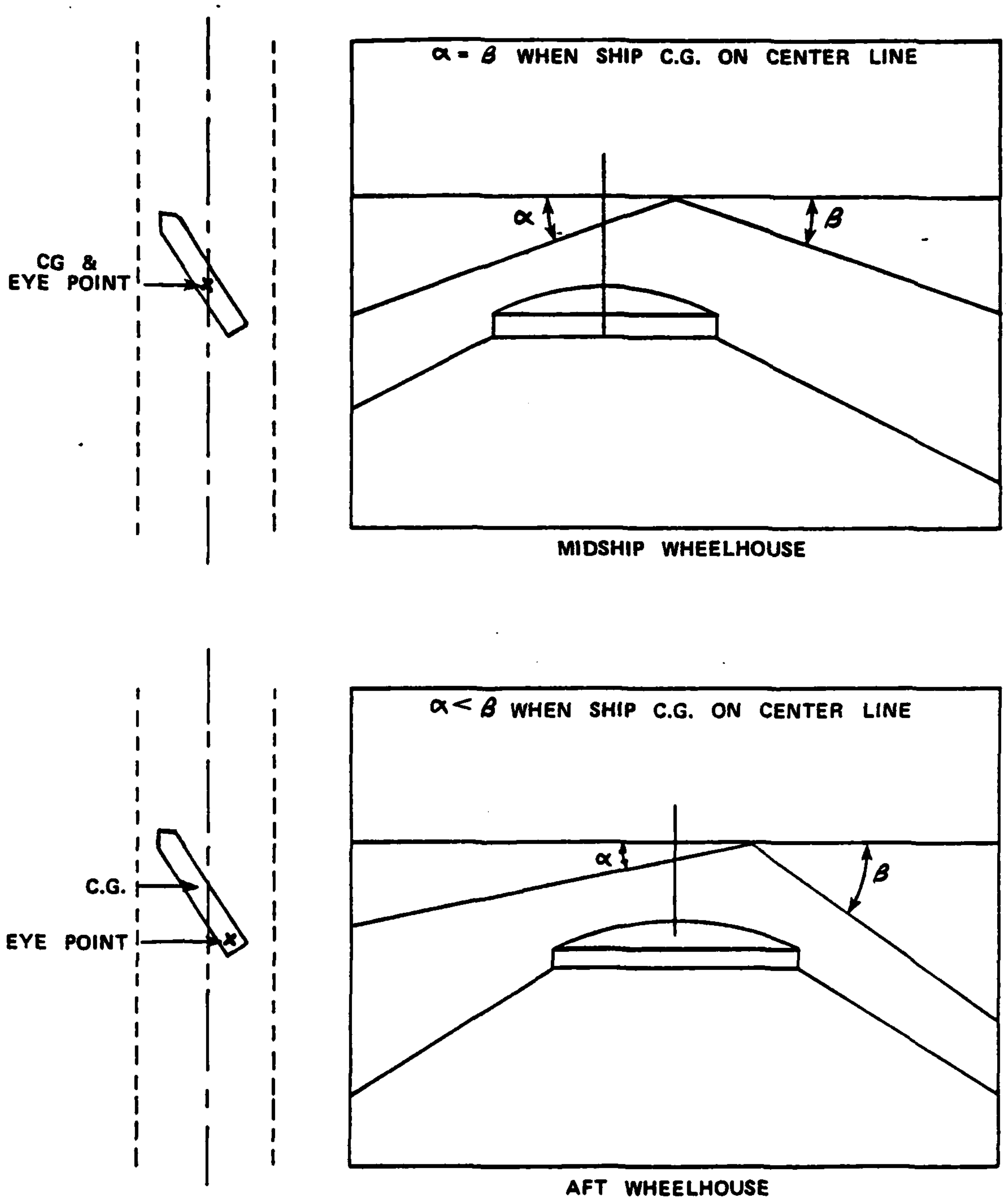


Figure A.11. Effect of Wheelhouse Location when Crabbing in a Channel

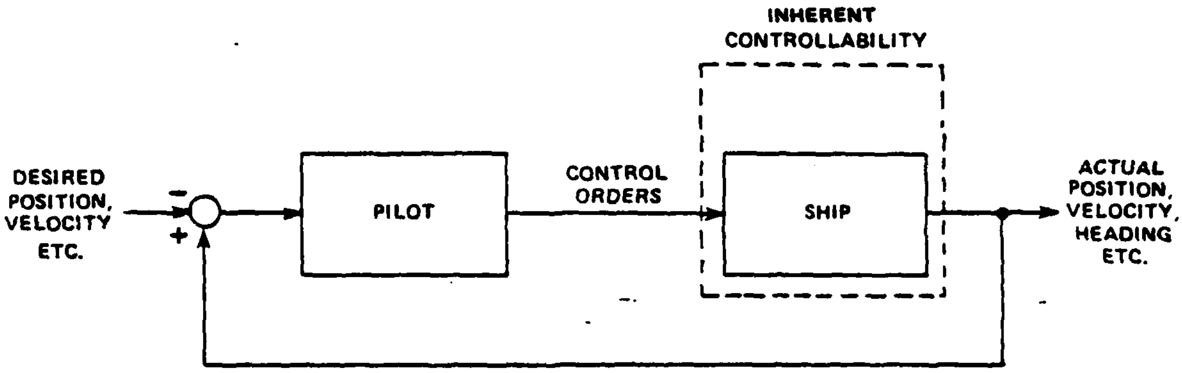


Figure A.12. Simplified Diagram of the Pilot/Ship Control Loop

Figure A.13. System Configuration for Simulated Sea Trials

Figure A.14 shows the response characteristics for a typical turning circle. Turning circles may be executed at various speeds, for different underkeel clearances, and with different rudder angles.

The data in Table A.4 indicate values of the turning circle parameters for the 30,000 dwt and 80,000 dwt tankers at 6 and 10 knots. Several properties of these data are evident. First, for shallow water, the tactical diameter, the advance, and the transfer at 6 knots and 10 knots are essentially equal. Second, the parameter values for the 30,000 and 80,000 dwt tankers are nearly equivalent for both speeds. Speed, therefore, does not appear to significantly affect the ship's track and, for the ship's selected, the size of the ship does not significantly alter the turning circle. Figures B-1 and B-2 in Appendix B show comparative track plots of the turning circle for the 30,000 and 80,000 dwt tanker respectively at 6 and 10 knots.

The impact of underkeel clearance is evident in Table A.5. All parameter values increase with a decrease in underkeel clearance. Figures B-3 and B-4 in Appendix B show comparative trackplots of the turning maneuvers for the 30,000 dwt and the 80,000 dwt tankers respectively for 1-foot and 600-foot underkeel clearances.

The effect of utilizing a smaller rudder angle is indicated by the data in Table A.6. Figures B.5 and B.6 in Appendix B show comparative plots of the turning maneuvers for the 30,000 dwt and 80,000 dwt tankers respectively for 20 degree and 35 degree rudder angles.

In summary, the turning maneuver data alone do not indicate a significant difference between the 30,000 dwt and 80,000 dwt tankers. Speed alone does not change the turning maneuver data. However, underkeel clearance and rudder angle utilized will impact the turning response.

A.3.2 ANALYSIS OF Z MANEUVERS

The Z maneuver is somewhat more complex than the turning circle maneuver and the response parameters are greater in number. This maneuver is executed as a series of rudder deflections based on the resultant heading changes. The typical Z maneuver is a 20/20 Z maneuver. From a straight line path with rudder amidships, the helm (rudder command) is deflected 20 degrees to the right. When the heading changes 20 degrees to the right of the initial heading, the helm is reversed to 20 degrees left. When the heading changes to 20 degrees left of the initial heading, the helm is reversed to 20 degrees right. The sequence may be continued any number of times. Variations in Z maneuvers may result from using larger or smaller helm deflections and reversing the helm at larger or smaller heading changes. As an example, a 10/2 Z maneuver uses 10-degree helm orders, reversing the helm when the heading is plus or minus 2 degrees of the initial heading. Z maneuvers may be conducted at various speeds and with various underkeel clearances.

The responses to Z maneuvers are relatively complex. Figure A.15 shows the rudder command, heading response, and crosstrack response for a typical Z maneuver. Several characteristics have been identified which may be of interest from a control point of view. They may be roughly associated with classic control response characteristics such as rise time, percent overshoot, maximum slewing rate, and lag and peak values.[3] The following list of parameters as identified in

[3] R. L. Cooper, R. L. Marino, and W. R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-1 Experiment."

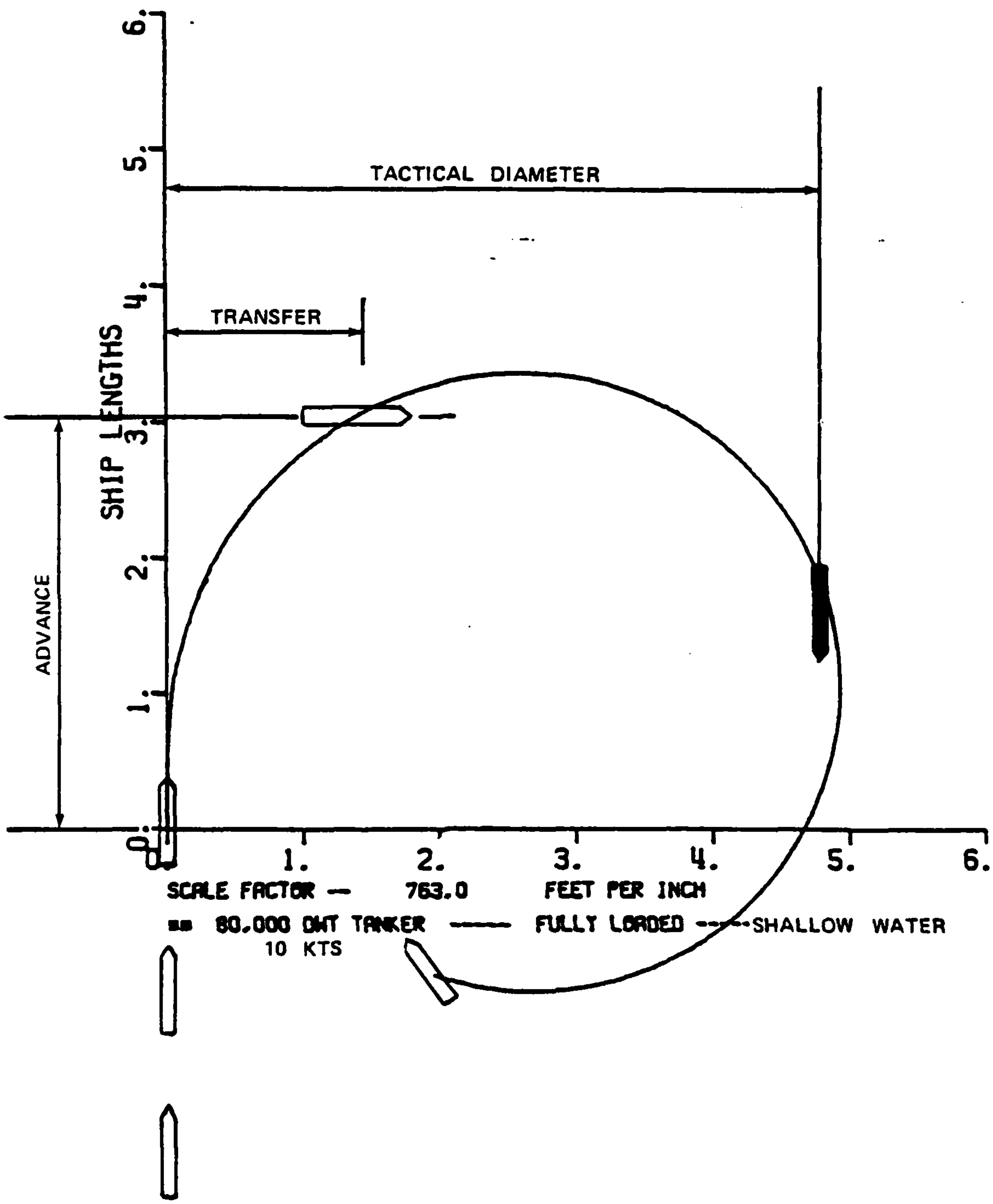


Figure A.14. Response Characteristics for a Turning Circle Maneuver, 35 Degree Right Rudder

TABLE A.4. COMPARISON OF TURN CIRCLES ACROSS SHIP SIZE AND SPEED WITH 1-FOOT UNDERKEEL CLEARANCE

SHIP SIZE	30,000 DWT		80,000 DWT	
SPEED (Knots)	6	10	6	10
TACTICAL DIAMETER (feet)	3625	3657	3753	3760
ADVANCE (feet)	2114	2192	2496	2558
TRANSFER (feet)	1700	1811	1790	1958

TABLE A.5. COMPARISON OF TURN CIRCLES ACROSS SHIP SIZE AND UNDERKEEL CLEARANCE FOR 6 KTS

SHIP SIZE	30,000 DWT		80,000 DWT	
UNDERKEEL CLEARANCE (feet)	1	600	1	600
TACTICAL DIAMETER (feet)	3625	2517	3753	2423
ADVANCE (feet)	2114	1811	2496	1988
TRANSFER (feet)	1700	1174	1790	946

TABLE A.6. COMPARISON OF TURN CIRCLES ACROSS SHIP SIZE AND RUDDER ANGLE WITH 1-FOOT UNDERKEEL CLEARANCE AT 6 KTS

SHIP SIZE	30,000 DWT		80,000 DWT	
RUDDER ANGLE (degrees)	20	35	20	35
TACTICAL DIAMETER (feet)	4666	3625	5650	3753
ADVANCE (feet)	2690	2114	3590	2496
TRANSFER (feet)	2268	1700	2745	1790

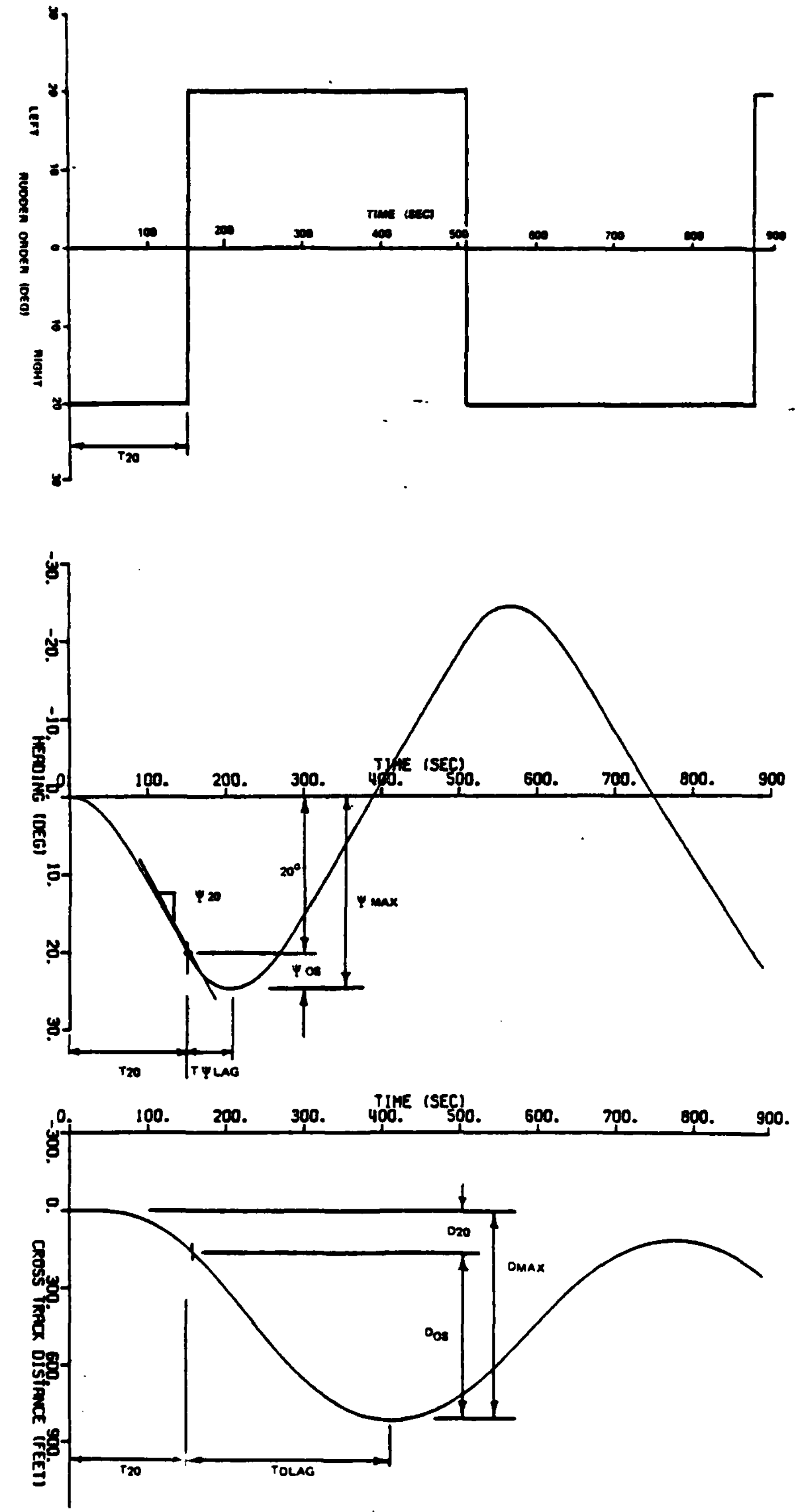


Figure A.15. Typical 20/20 'Z' Maneuver

Figure A.15 can be compiled for Z maneuvers. Other parameters analyzed for the Z maneuver correlated with those listed below.

Rise Time (T_{20}) = Time interval for the heading to change to 20 degrees right of initial heading measured from the maneuver initiation (seconds)

Max Heading Excursion (ψ_{MAX}) = The maximum heading deviation from the initial heading for the first rudder deflection (degrees)

Heading Overshoot (% ψ_{OS}) = The overshoot in heading which occurs after the rudder command is reversed (percent):

$$\% \psi_{OS} = 100 \psi_{OS}/20 \text{ where } \psi_{OS} = \psi_{MAX} - 20$$

Heading Lag ($T_{\psi LAG}$) = The time interval between the first reversal of the rudder command and the maximum heading difference from the initial heading (seconds)

Slew Rate ($\dot{\psi}_{20}$) = The maximum turning rate achieved in the maneuver. It occurs at the point where the ship's heading has just reached 20 degrees right of the initial heading (degrees/second)

Max Crosstrack Excursion (D_{MAX}) = The maximum crosstrack displacement from the initial ship's track. It is measured following the first rudder reversal (feet)

Crosstrack Overshoot (%D_{OS}) = The overshoot in distance which occurs after the rudder command is reversed (percent): %D_{OS} = 100 D_{OS}/D_{20} where $D_{OS} = D_{MAX} - D_{20}$ and D_{20} is the crosstrack displacement when the heading change first reaches 20 degrees to the right of the initial heading

Displacement Lag (T_{DLAG}) = The time interval between the first reversal of the rudder command and the maximum crosstrack displacement from the initial track (feet)

It is instructive to group the maneuver variables for comparison of various experimental conditions. Three groups have been selected.

Turn Response Variables:

Rise Time: T_{20}

Slew Rate: $\dot{\psi}_{20}$

Heading Lag: $T_{\psi LAG}$

Displacement Lag: T_{DLAG}

Heading Response Variables:

Max Heading Excursion: ψ_{MAX}

% Heading Overshoot: % ψ_{OS}

Track Response Variables:

Max Crosstrack Displacement: D_{MAX}

% Crosstrack Overshoot: %D_{OS}

The Turn Response Variables describe the time response, the system time lag intervals and the rate characteristics of turning. These variables describe the length

of time the pilot must anticipate his control actions and/or the time lag in system response to control orders. The time domain was selected for presentation of the turn response variables because traditional man-machine system analysis has addressed the control problem associated with time delays in the machine.[4] *In the piloting situation, however, alongtrack distance traveled may be important* since these distances are observable and buoy positions relative to the ship's length may be an important perceptual cue for initiating maneuvers and corrective actions. Turn response variable may, therefore, also be expressed as alongtrack distance traveled during the stated time intervals. The time domain variables may be changed to alongtrack distance units through multiplication by ship's average speed. Such variables are said to be expressed in the distance domain.

The Heading Response Variables describe the magnitude and overshoot of the ship's heading following the first rudder reversal. This response is of interest because it is hypothesized that pilots control the ship's track by controlling the ship's heading at various positions along the channel and through the turn. The overshoot data, perhaps, indicate how reliably the pilot can achieve the desired heading by issuing rudder orders.

The Track Response Variables describe the magnitude and overshoot in the crosstrack position of the ship in response to manipulation of the helm. Ultimately, the pilot must control crosstrack position to achieve the desired transit. Control of these variables is achieved indirectly through helm orders and indirectly through control of the ship's heading.

The data in Table A.7 summarize the response parameters for 20/20 Z maneuvers *for both the 30,000 dwt and 80,000 dwt tankers at 6 and 10 knots.* The individual parameters are grouped as turn response, heading response, and track response variables. The turn response variables are indicated in both the time domain and the distance domain.

The data in Table A.7 show several important relationships between experimental conditions:

a. *A speed increase (for either ship) affects only the turn response variables in the time domain.* The track response variables, the heading response variables and the turn response variables in distance domain are relatively unchanged by changes in speed.

b. *The heading response variables are nearly identical between the 30,000 dwt and 80,000 dwt ships.*

c. *Between the two ships at equal speeds, the turn response variables and the track response variables are different in magnitude.* The 80,000 dwt versus the 30,000 dwt tanker exhibits longer rise and lag times, slower maximum turning rates, travels more distance between initiation of orders, achieves a greater crosstrack displacement, and overshoots in crosstrack distance a greater amount.

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[4] R. B. Cooper, K. L. Marino, and W. R. Bertsche. "Simulator Evaluation of Electronic Radio Aids to Navigation Displays, the RA-2 Experiment." U.S. Coast Guard, Washington, D.C., April 1981.

TABLE A.7. COMPARISON OF 20/20 "Z" MANEUVERS ACROSS SHIP SIZE AND SPEED FOR 1-FOOT UNDERKEEL CLEARANCE

	30,000 DWT TANKER		80,000 DWT TANKER	
	6 KNOTS	10 KNOTS	6 KNOTS	10 KNOTS
Turn Response Variables				
Rise time: T_{20}	110 sec	69 sec	150 sec	92 sec
Heading leg: $T_{\psi\,LAG}$	30 sec	21 sec	60 sec	38 sec
Displacement lag: T_{DLAG}	160 sec	101 sec	260 sec	168 sec
Slew rate: $\dot{\psi}_{MAX}$	0.25 deg/sec	0.4 deg/sec	0.18 deg/sec	0.3 deg/sec
Distance traveled for T_{20}	1097 ft	1140 ft	1476 ft	1511 ft
Distance traveled to $T_{\psi\,LAG}$	292 ft	336 ft	559 ft	589 ft
Distance traveled for T_{DLAG}	1546 ft	1601 ft	2356 ft	2527 ft
Maximum heading change per distance traveled	0.026 deg/ft	0.025 deg/ft	0.019 deg/ft	0.019 deg/ft
Heading Response Variables				
Maximum heading excursion: ψ_{MAX}	24.4 deg	25.6 deg	24.8 deg	25.8 deg
Heading overshoot: $\%\psi_{OS}$	22%	28%	24%	29%
Track Response Variable				
Maximum crosstrack excursion: D_{MAX}	533 ft	589 ft	810 ft	865 ft
Crosstrack overshoot: $\%D_{OS}$	330%	367%	459%	492%

d. *For the unique case of a 30,000 dwt tanker at 6 knots versus the 80,000 dwt at 10 knots the turn response variables in the time domain are approximately equal but all distance related variables remain different.* The track plots of the heading response and track response as a function of speed are shown in Figures B.7 through B.10 in Appendix B for the 30,000 dwt and 80,000 dwt tankers respectively. The 6 and 10-knot cases are indicated.

Plots of the heading response and track response as a function of ship size are shown in Figures B.11 and B.12 in Appendix B for 6 knots.

The special comparison of the 30,000 dwt tanker at 6 knots versus the 80,000 dwt tanker at 10 knots is shown in plots of heading and track responses in Figures B.13 and B.14 in Appendix B.

The comparison of Z maneuvers at various underkeel depths provides some insight into the impact of channel depth on the ship's response. Table A.8 lists the Z maneuver response data compiled for both ships with either 1-foot underkeel clearance or an excess of 600-foot underkeel clearance. These data indicate that underkeel clearance has a greater effect on the response variables of the 80,000 dwt tanker versus the 30,000 dwt. In either case, however, no response variable changes more than approximately 15 percent. As compared to the turning circles discussed in section A.2, this change would appear to be relatively small such that the statement could be made that the Z maneuver response characteristics are relatively insensitive to underkeel clearance. Figures B.15 through B.18 in Appendix B show the heading and track responses with the alternate underkeel clearances for the 30,000 dwt and 80,000 dwt tankers, respectively.

In summary, a comparison of 20/20 Z maneuver data identified that the change in speed for both ships results in changes in the turn response variables only in the time domain. If these variables are considered in the distance domain, speed does not significantly affect the inherent controllability of the ship. A comparison of ships identified major differences in both turn response and track response variables for conditions of equal speed. However, in the special case of the 30,000 dwt tanker at 6 knots versus the 80,000 dwt tanker at 10 knots, the difference in ships is only in the track response and in the distance domain of the turn response variables. Finally, a comparison of Z maneuvers for both ships with alternate underkeel clearance revealed that this clearance had little effect on the response variables.

TABLE A.8. COMPARISON OF 20/20 Z MANEUVERS ACROSS SHIP SIZE AND UNDERKEEL CLEARANCE FOR SHIP'S SPEED OF 6 KTS.

	30,000 DWT TANKER		80,000 DWT TANKER	
	1 ft underkeel	600 ft underkeel	1 ft underkeel	600 ft underkeel
Turn Response Variables				
Rise time: T_{20} (seconds)	110	93	150	125
Heading lag: $T_{\psi LAG}$ (seconds)	30	40	60	75
Displacement lag: T_{DLAG} (seconds)	160	160	260	300
Slew rate: ψ^{ρ}_{MAX}	0.025 deg/sec	0.31 deg/sec	0.18 deg/sec	0.25 deg/sec
Distance traveled for: T_{20} (feet)	1097	950	1476	1253
Distance traveled for: $T_{\psi LAG}$ (feet)	292	406	559	708
Distance traveled for: T_{DLAG} (feet)	1546	1646	2356	2784
Maximum heading change per distance traveled	0.026 deg/ft	0.030 deg/ft	0.019 deg/ft	0.0257 deg/ft
Heading Response Variables				
Maximum heading excursion: ψ_{MAX} (degrees)	24.4	25.9	24.8	28.7
Heading overshoot: $\%\psi_{OS}$	22	30	24	44
Track Response Variable				
Maximum crosstrack excursion: D_{MAX} (feet)	533	523	810	940
Crosstrack overshoot: $\%D_{OS}$	530	545	459	1100

APPENDIX B

This appendix contains plots of ship's tracks and response data recorded during simulated sea trial maneuvers. Turning circle and Z maneuvers are evaluated.

Two ship sizes are evaluated:

30,000 dwt tanker, 34-foot draft.
80,000 dwt tanker, 39-foot draft.

The trial maneuvers were typically conducted under the following conditions.

Speed:	6 knots or 10 knots
Underkeel clearance:	1 foot or > 600 feet

The figure contents are as follows:

Turning Circle Maneuvers

Figure B.1	6 versus 10 knots, 30,000 dwt, 1-foot underkeel
Figure B.2	6 versus 10 knots, 80,000 dwt, 1-foot underkeel
Figure B.3	1-foot versus >600-foot underkeel, 30,000 dwt, 6 knots
Figure B.4	1-foot versus >600-foot underkeel, 80,000 dwt, 6 knots
Figure B.5	20 versus 35 degrees rudder, 30,000 dwt, 6 knots, 1-foot underkeel
Figure B.6	20 versus 35 degrees rudder, 80,000 dwt, 6 knots, 1-foot underkeel.

20/20 Z Maneuvers

Figure B.7	Heading Response: 6 versus 10 kts, 30,000 dwt, 1-foot underkeel
Figure B.8	Track Response: 6 versus 10 kts, 30,000 dwt, 1-foot underkeel
Figure B.9	Heading Response: 6 versus 10 kts, 80,000 dwt, 1-foot underkeel
Figure B.10	Track Response: 6 versus 10 kts, 80,000 dwt, 1-foot underkeel
Figure B.11	Heading Response: 30,000 versus 80,000 dwt, 6 knots, 1-foot underkeel
Figure B.12	Track Response: 30,000 versus 80,000 dwt, 6 knots, 1-foot underkeel
Figure B.13	Heading Response: 30,000 dwt at 6 knots versus 80,000 dwt at 10 knots, 1-foot underkeel
Figure B.14	Track Response: 30,000 dwt at 6 knots versus 80,000 dwt at 10 knots, 1-foot underkeel
Figure B.15	Heading Response: 1 versus >600 foot underkeel, 30,000 dwt, 6 knots
Figure B.16	Track Response: 1 versus >600 foot underkeel, 30,000 dwt, 6 knots
Figure B.17	Heading Response: 1 versus >600 foot underkeel, 80,000 dwt, 6 knots
Figure B.18	Track Response: 1 versus >600 foot underkeel, 80,000 dwt, 6 knots

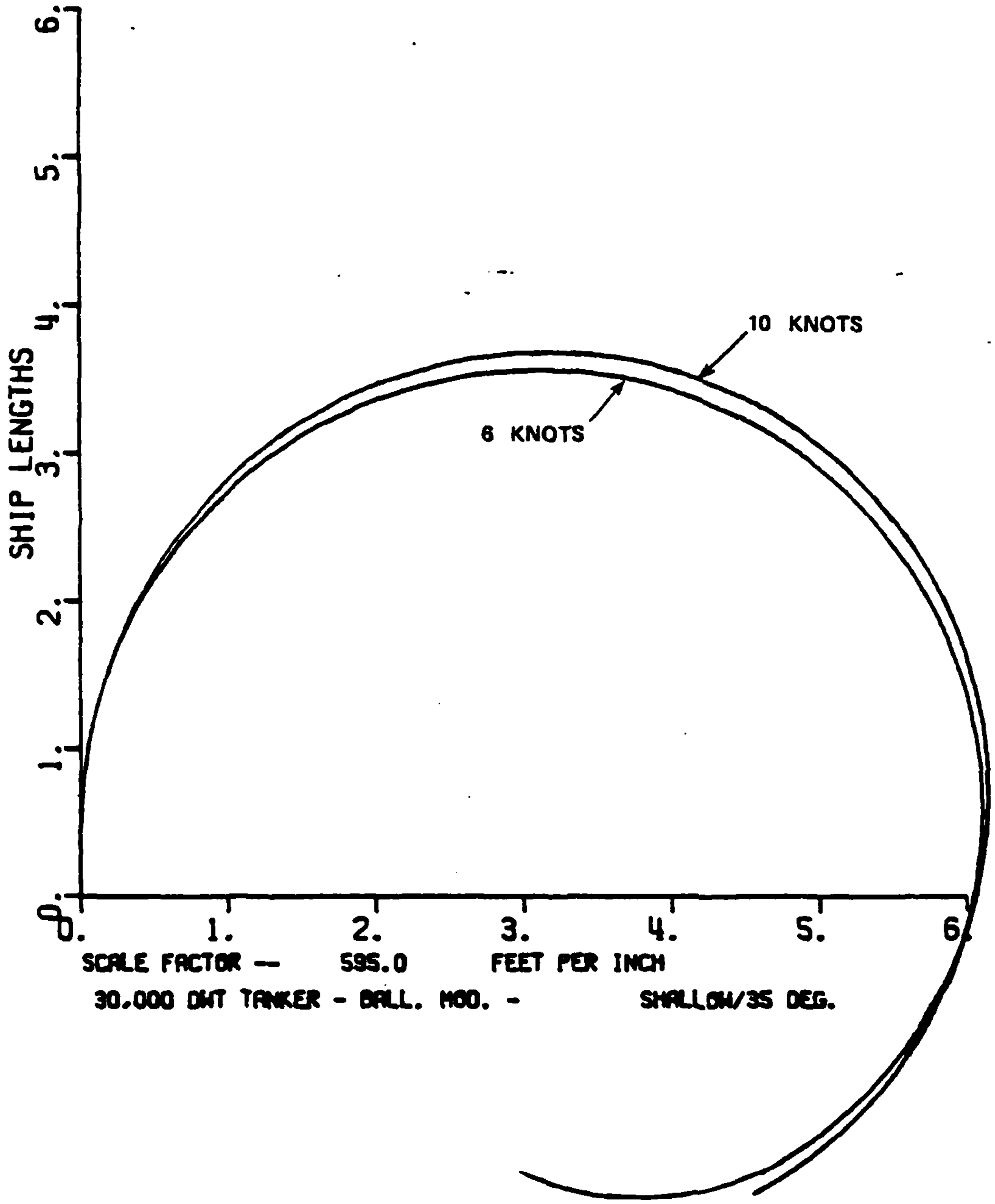

6.
5.
4.
3.
2.
1.
0.
SHIP LENGTHS
10 KNOTS
6 KNOTS
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER - BALL. MOD. - SHALLOW/35 DEG.

Figure B-1

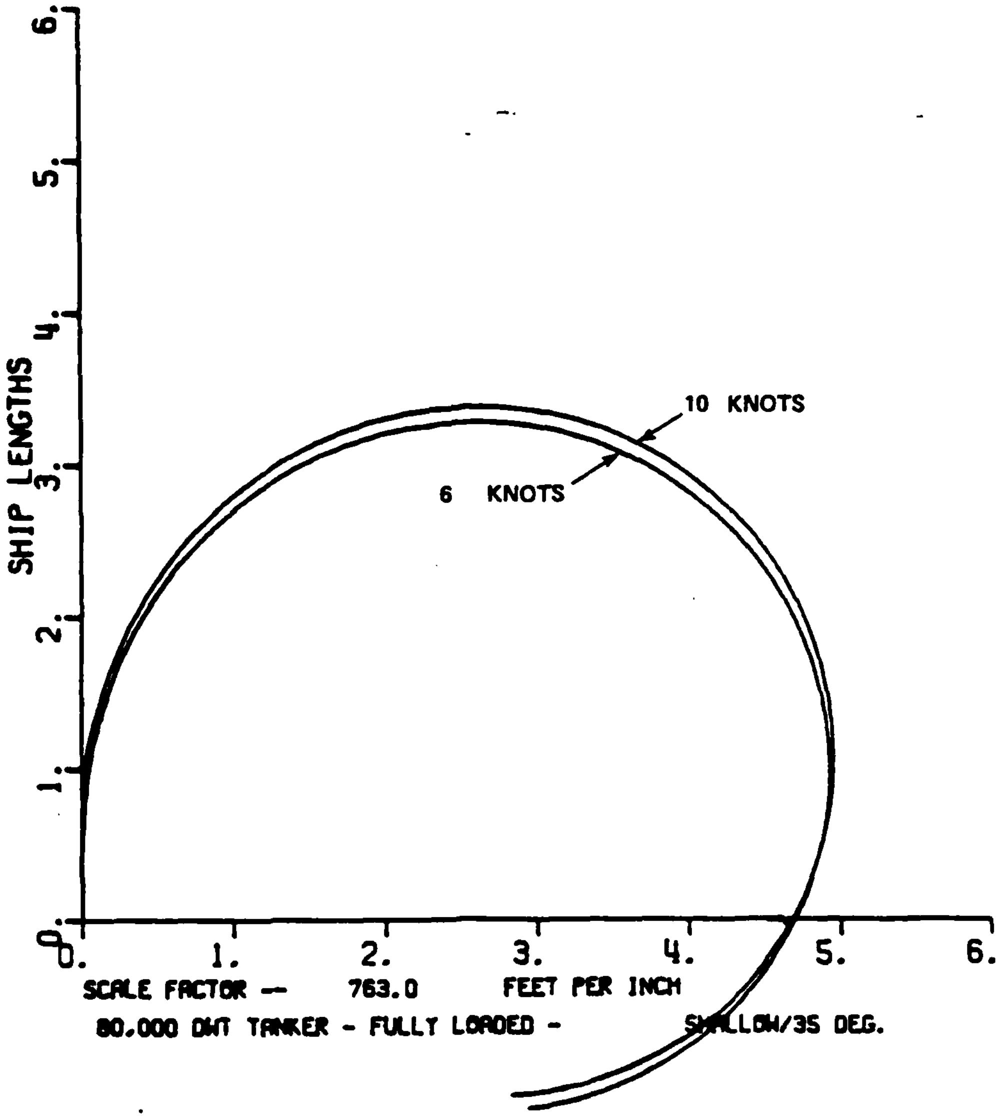
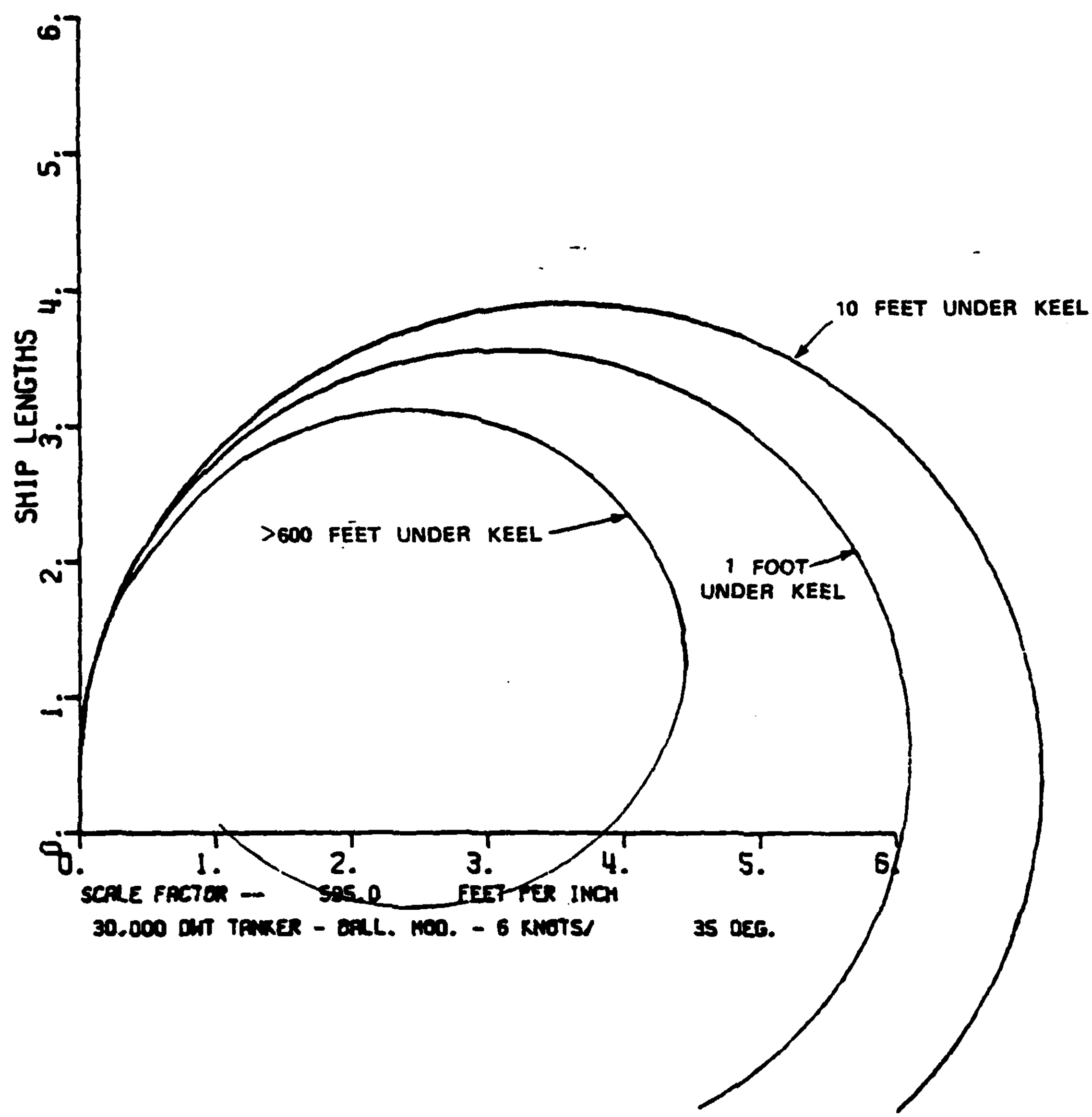
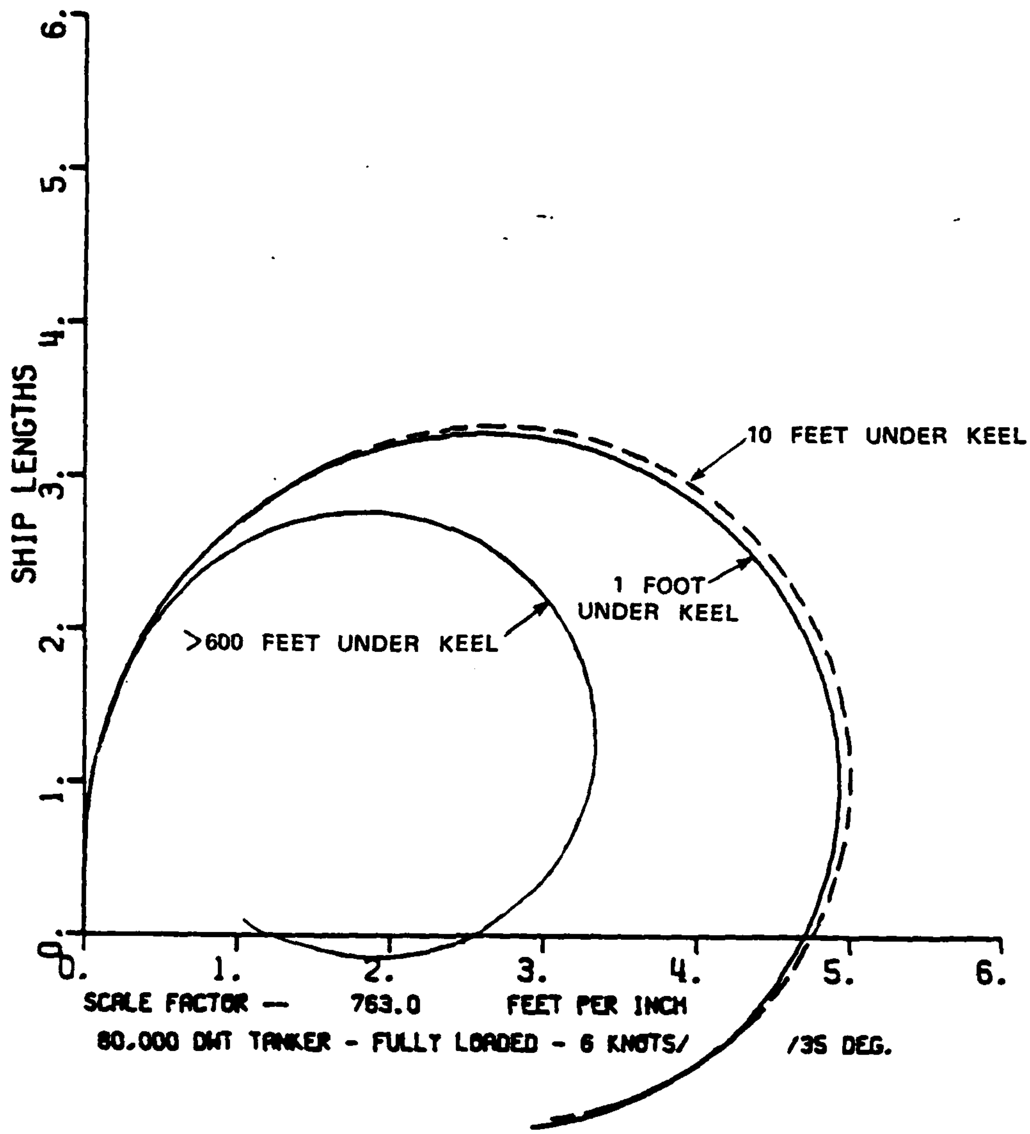

SHIP LENGTHS
0.
1.
2.
3.
4.
5.
6.
10 KNOTS
6 KNOTS
SCALE FACTOR -- 763.0 FEET PER INCH
80,000 DWT TANKER - FULLY LOADED - SHALLOW/35 DEG.

Figure B-2



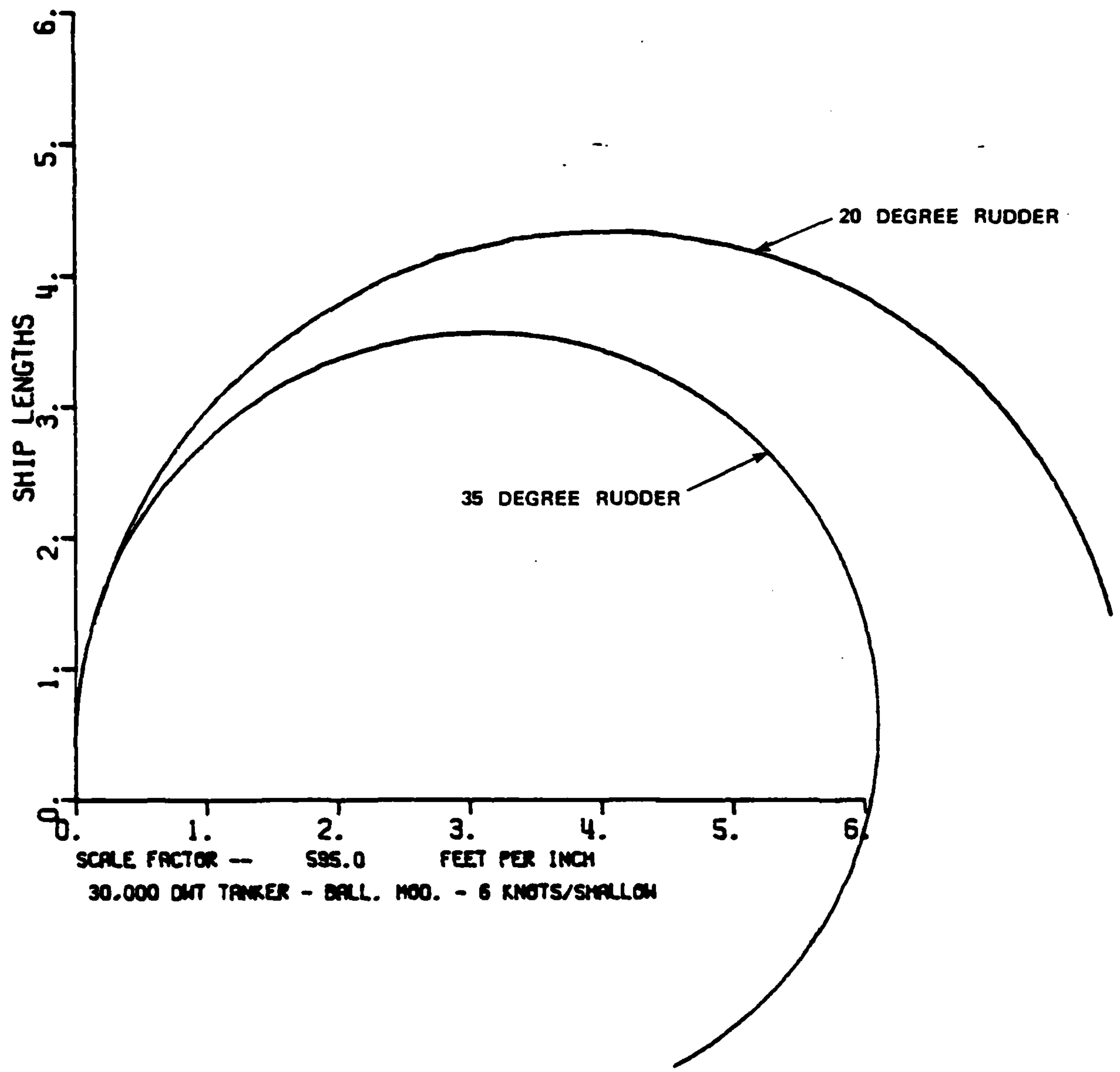
6.
5.
4.
3.
2.
1.
0.
SHIP LENGTHS
10 FEET UNDER KEEL
>600 FEET UNDER KEEL
1 FOOT
UNDER KEEL
0.
1.
2.
3.
4.
5.
6.
SCALE FACTOR -- 585.0 FEET PER INCH
30,000 DWT TANKER - BALL. MOD. - 6 KNOTS/ 35 DEG.

Figure B-3



SHIP LENGTHS
0.
1.
2.
3.
4.
5.
6.
10 FEET UNDER KEEL
1 FOOT UNDER KEEL
>600 FEET UNDER KEEL
SCALE FACTOR — 763.0 FEET PER INCH
80.000 DWT TANKER - FULLY LOADED - 6 KNOTS/ /35 DEG.

Figure B-4



SHIP LENGTHS
0.
1.
2.
3.
4.
5.
6.
20 DEGREE RUDDER
35 DEGREE RUDDER
SCALE FACTOR -- 595.0 FEET PER INCH
30,000 DWT TANKER - BALL. MOD. - 6 KNOTS/SHALLOW

Figure B-5

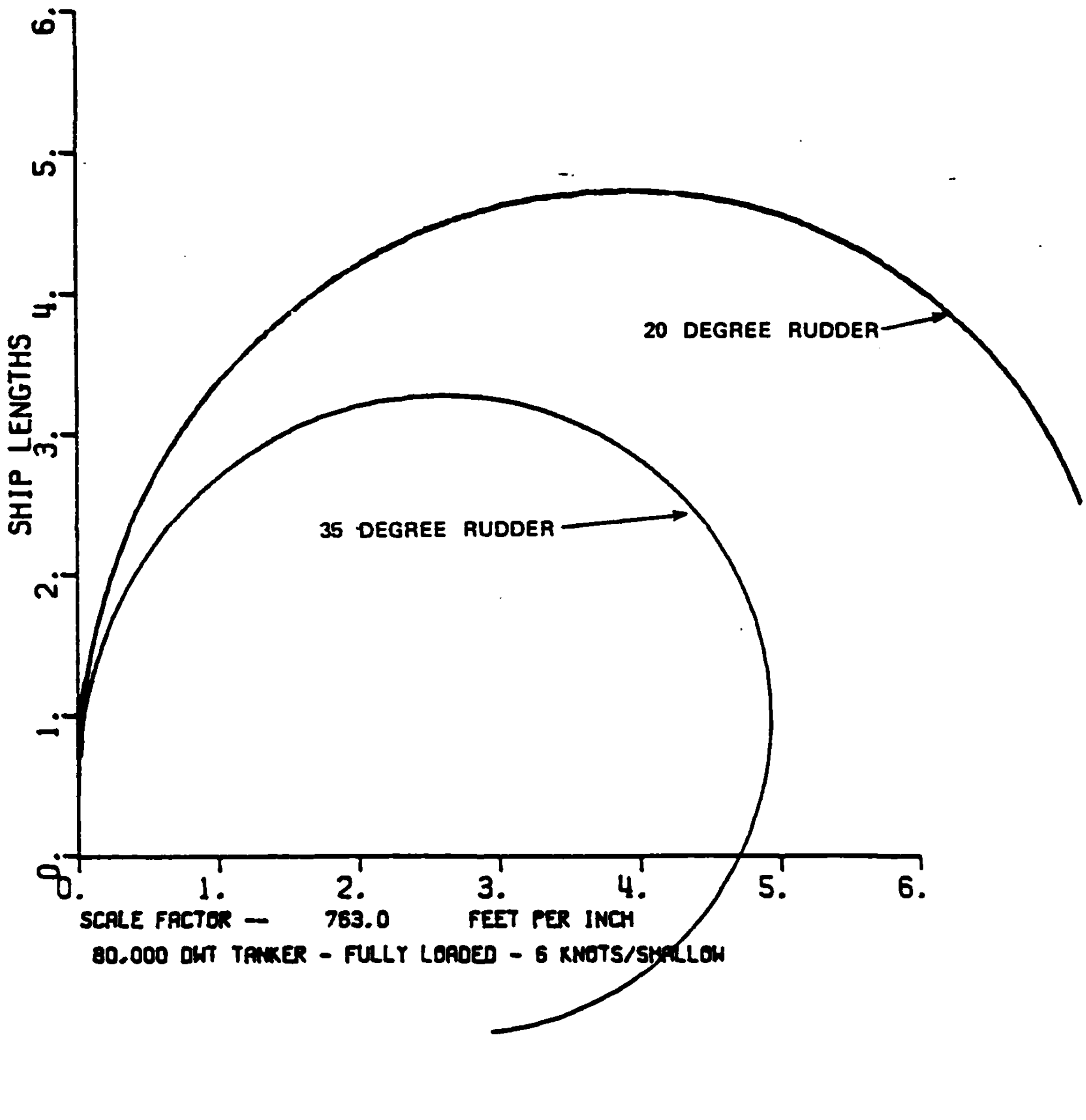
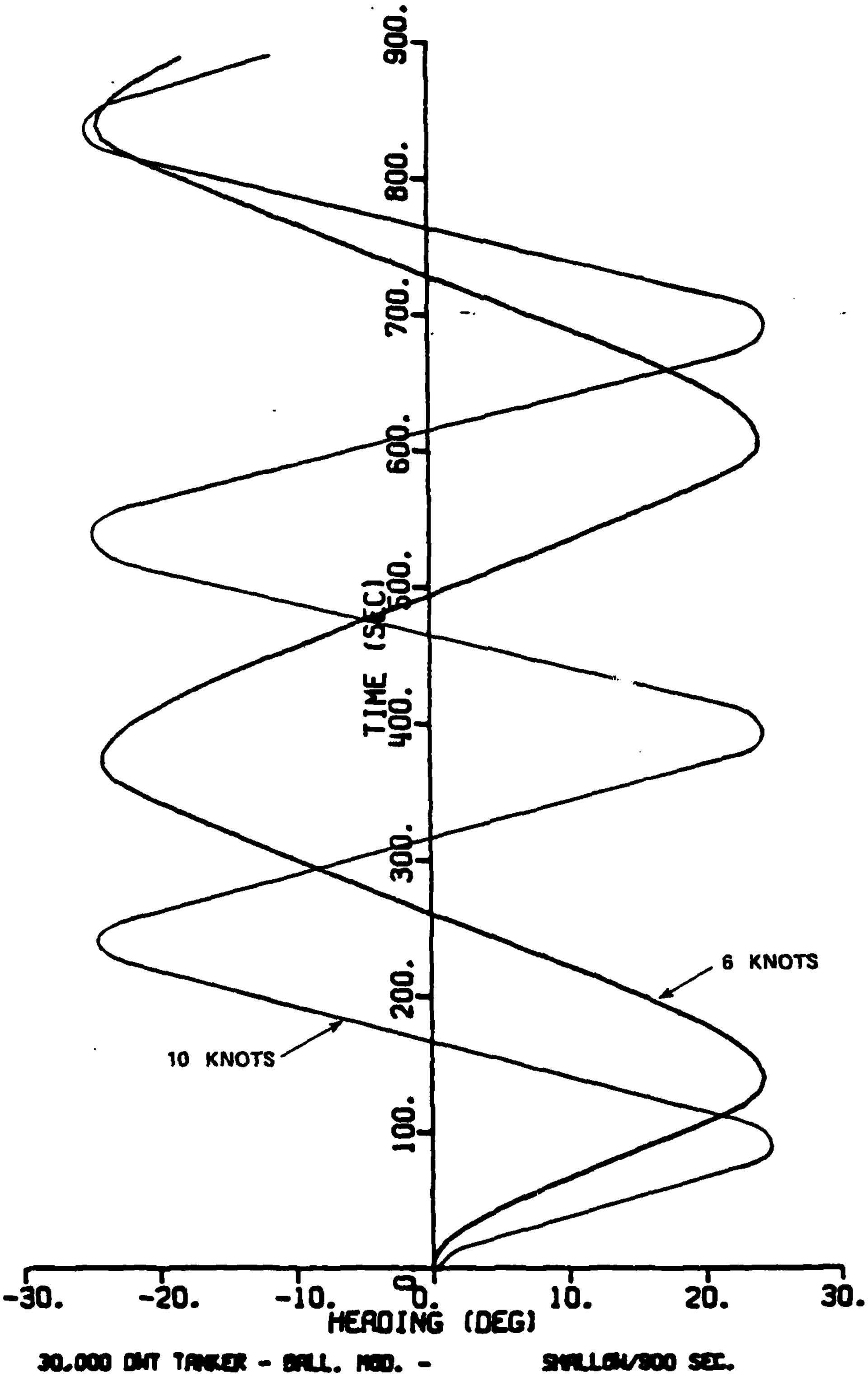

SHIP LENGTHS
0.
1.
2.
3.
4.
5.
6.
20 DEGREE RUDDER
35 DEGREE RUDDER
SCALE FACTOR — 763.0 FEET PER INCH
80,000 DWT TANKER - FULLY LOADED - 6 KNOTS/SHALLOW

Figure B-6



TIME (SEC)
900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
-30.
-20.
-10.
0.
10.
20.
30.
HEADING (DEG)
6 KNOTS
10 KNOTS
30.000 DWT TANKER - BALL. MOD. - SHALLOW/900 SEC.

Figure B-7

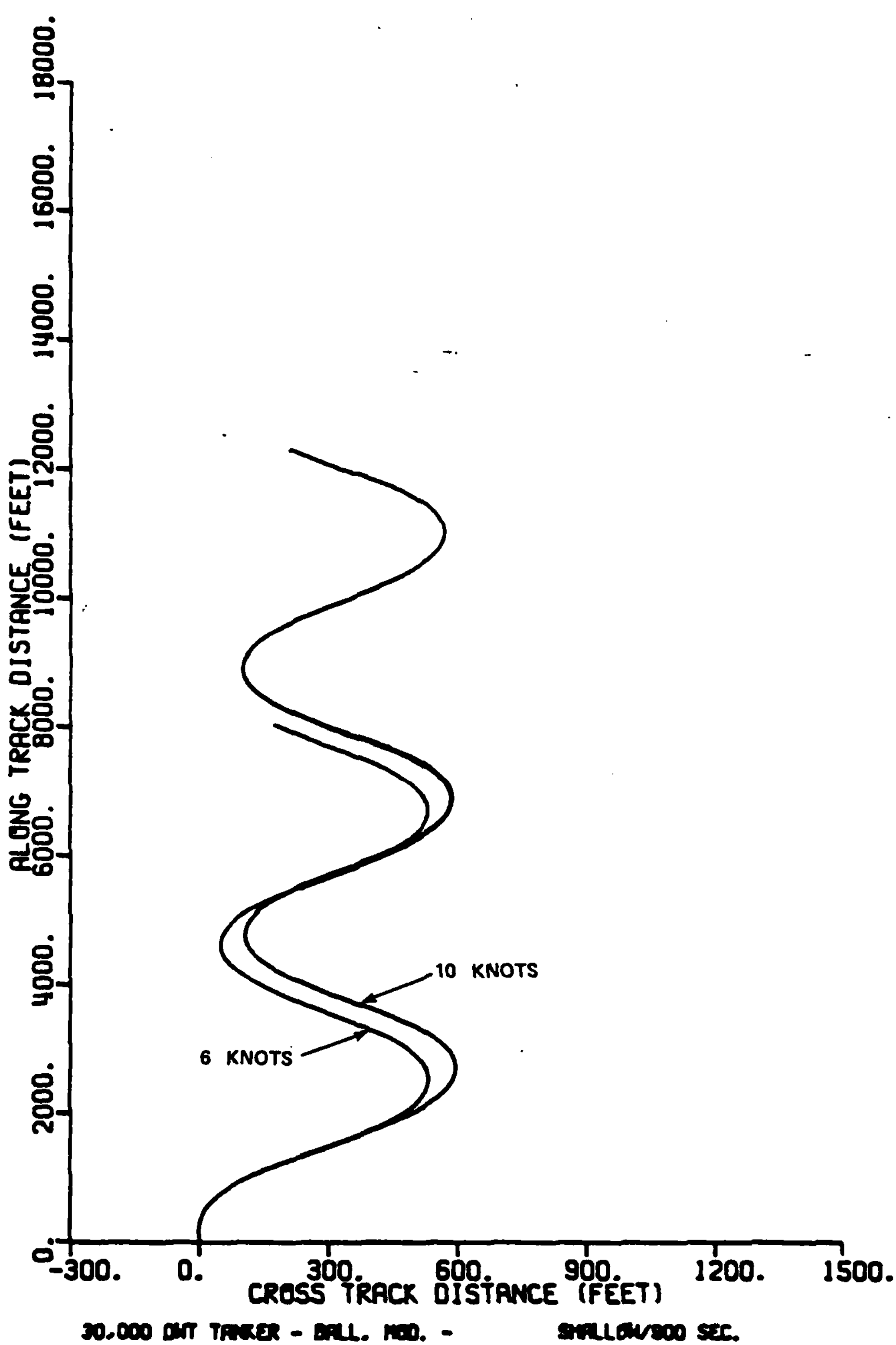
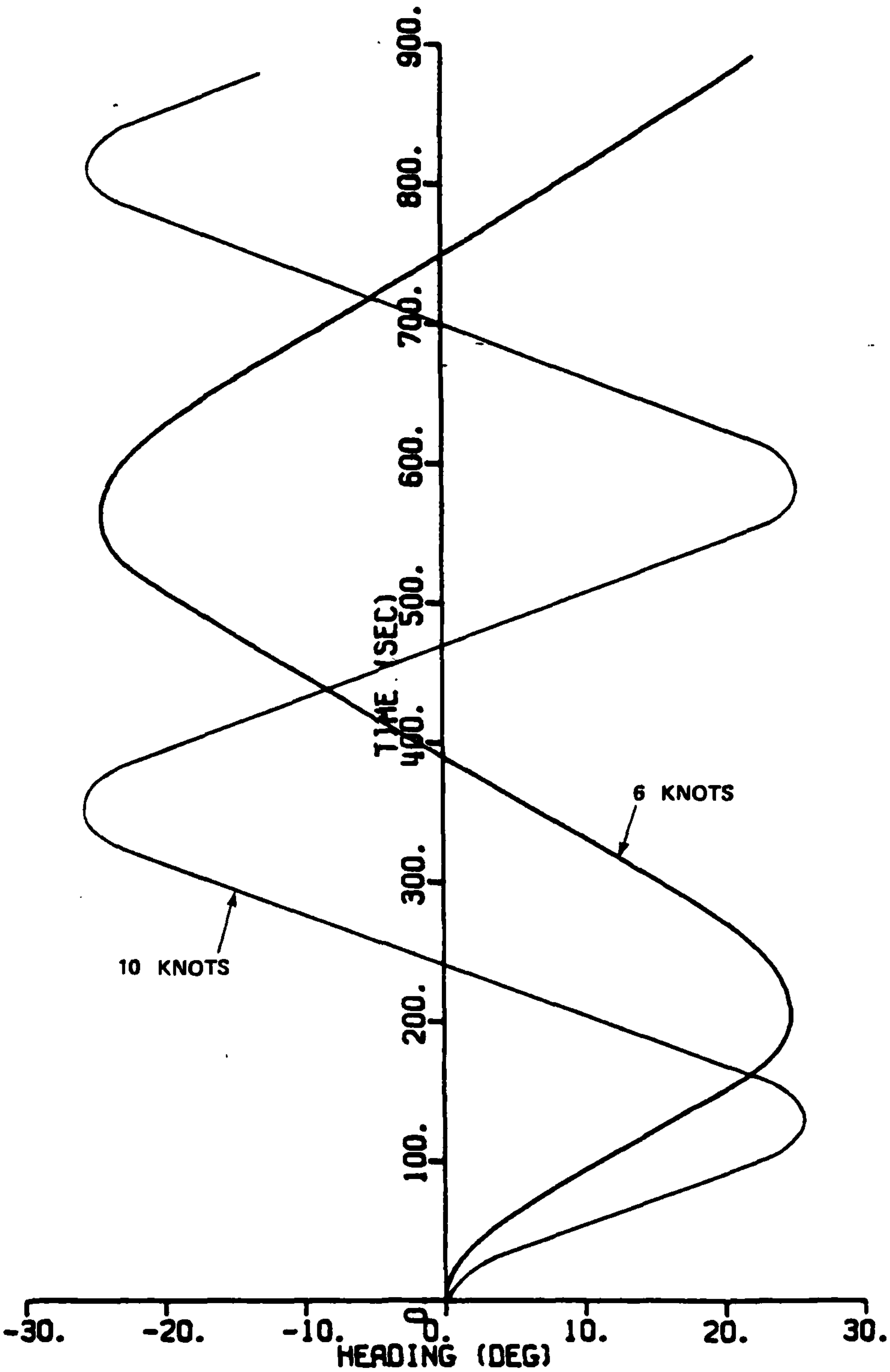

ALONG TRACK DISTANCE (FEET)
0.
2000.
4000.
6000.
8000.
10000.
12000.
14000.
16000.
18000.
-300.
0.
300.
600.
900.
1200.
1500.
CROSS TRACK DISTANCE (FEET)
10 KNOTS
6 KNOTS
30,000 DWT TANKER - BALL. MOD. - SHALLOW/900 SEC.

Figure B-8



80,000 DWT TANKER - FULLY LOADED - SHALLOW/900 SEC.

Figure B-9

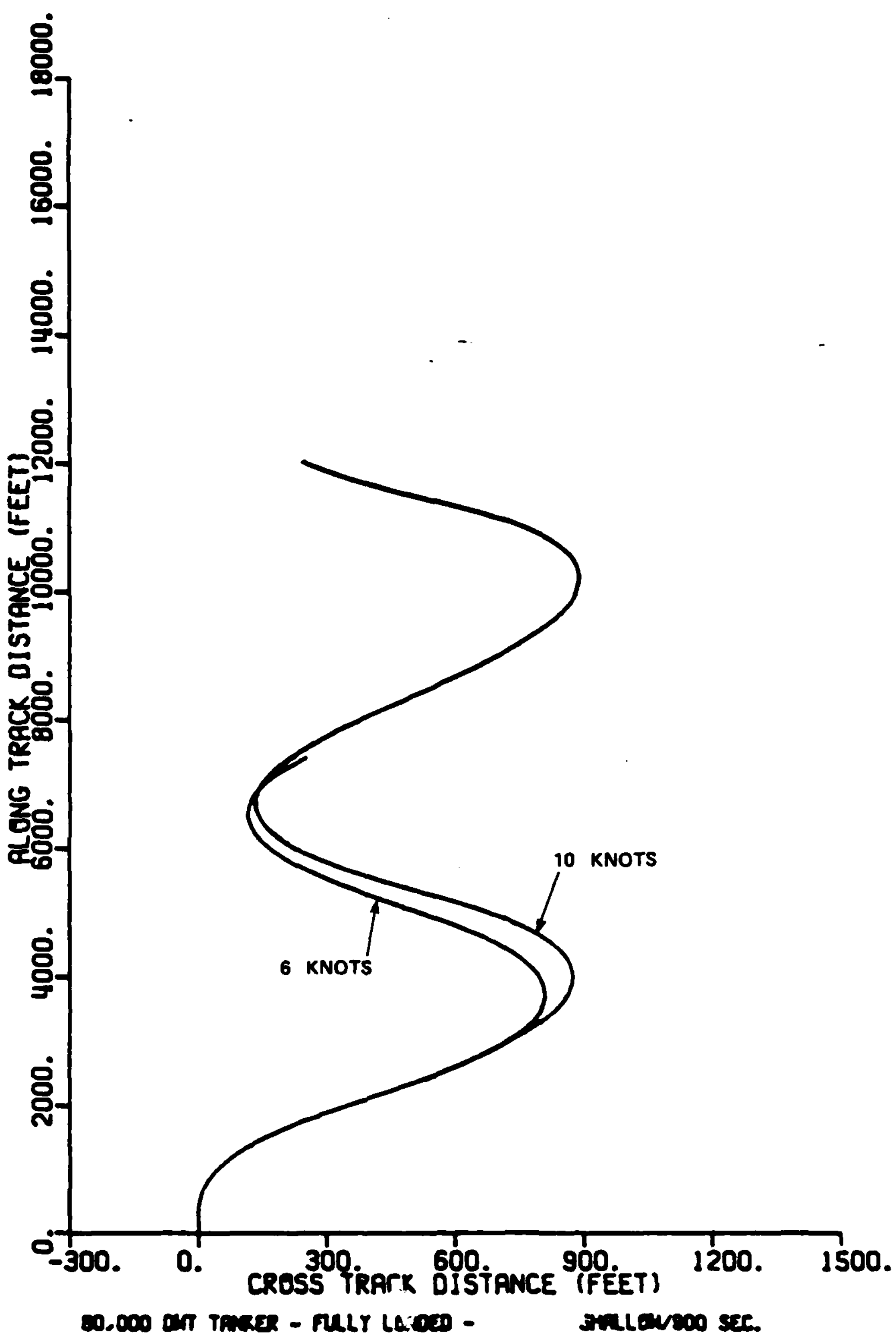

ALONG TRACK DISTANCE (FEET)
0.
2000.
4000.
6000.
8000.
10000.
12000.
14000.
16000.
18000.
-300.
0.
300.
600.
900.
1200.
1500.
CROSS TRACK DISTANCE (FEET)
10 KNOTS
6 KNOTS
80,000 DWT TANKER - FULLY LOADED - SHALLOW/900 SEC.

Figure B-10

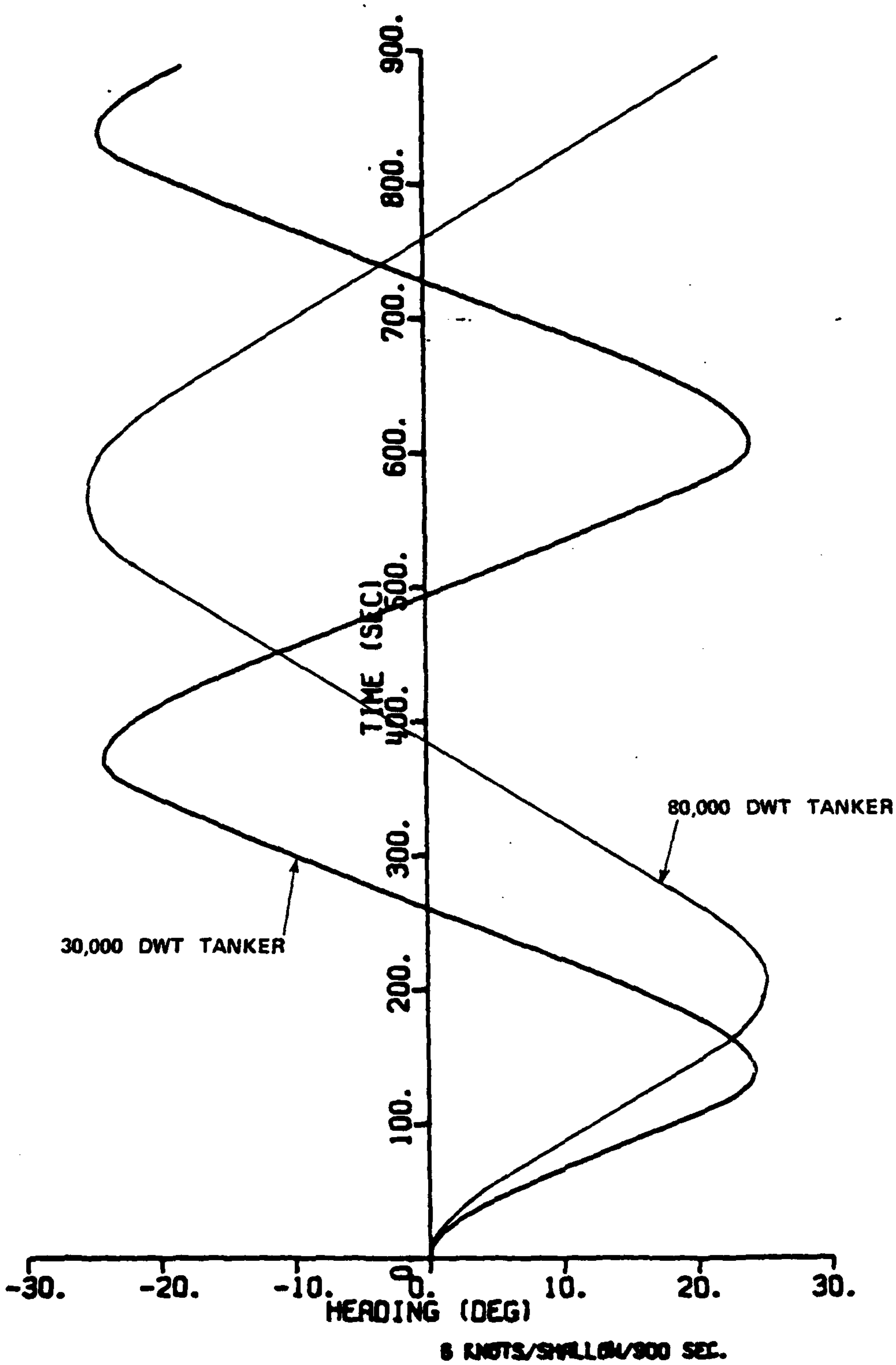

900.
800.
700.
600.
500.
TIME (SEC)
400.
300.
200.
100.
0.
80,000 DWT TANKER
30,000 DWT TANKER
-30.
-20.
-10.
0.
10.
20.
30.
HEADING (DEG)
8 KNOTS/SHALLOW/900 SEC.

Figure B-11

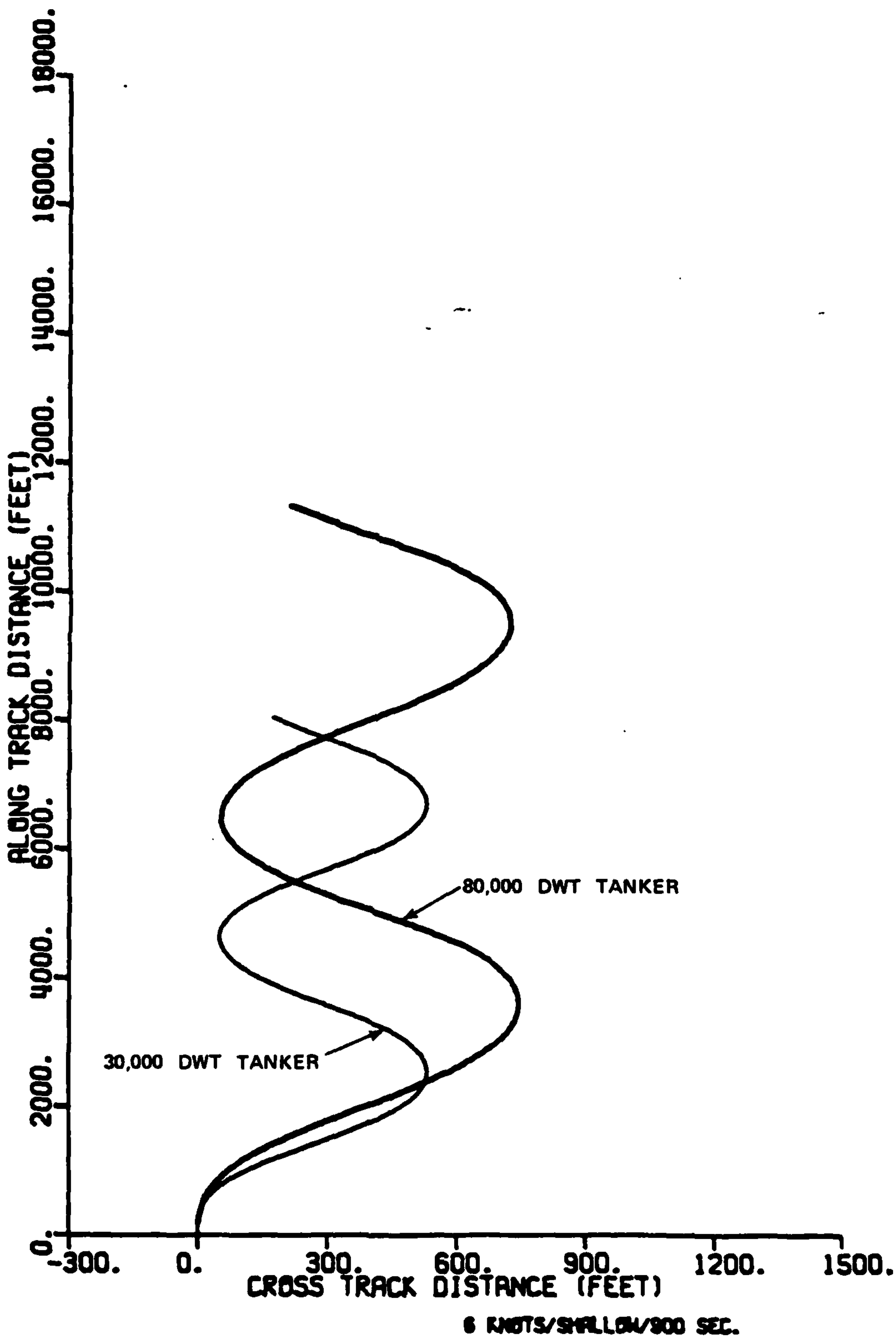

ALONG TRACK DISTANCE (FEET)
0.
2000.
4000.
6000.
8000.
10000.
12000.
14000.
16000.
18000.
-300.
0.
300.
600.
900.
1200.
1500.
CROSS TRACK DISTANCE (FEET)
80,000 DWT TANKER
30,000 DWT TANKER
6 KNOTS/SHALLOW/900 SEC.

Figure B-12

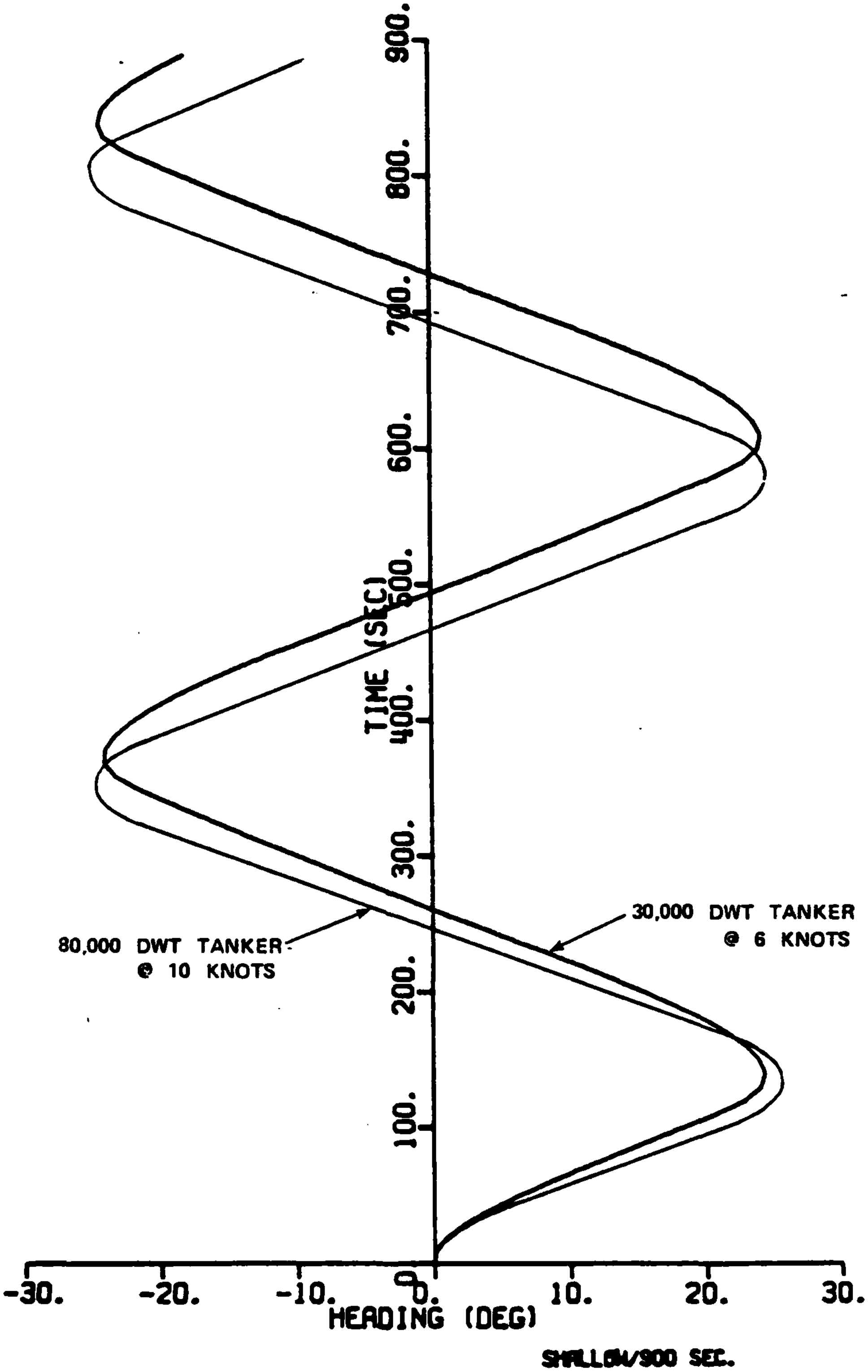

TIME (SEC)
900.
800.
700.
600.
500.
400.
300.
200.
100.
0
80,000 DWT TANKER
@ 10 KNOTS
30,000 DWT TANKER
@ 6 KNOTS
-30.
-20.
-10.
0.
10.
20.
30.
HEADING (DEG)
SHALLOW/900 SEC.

Figure B-13

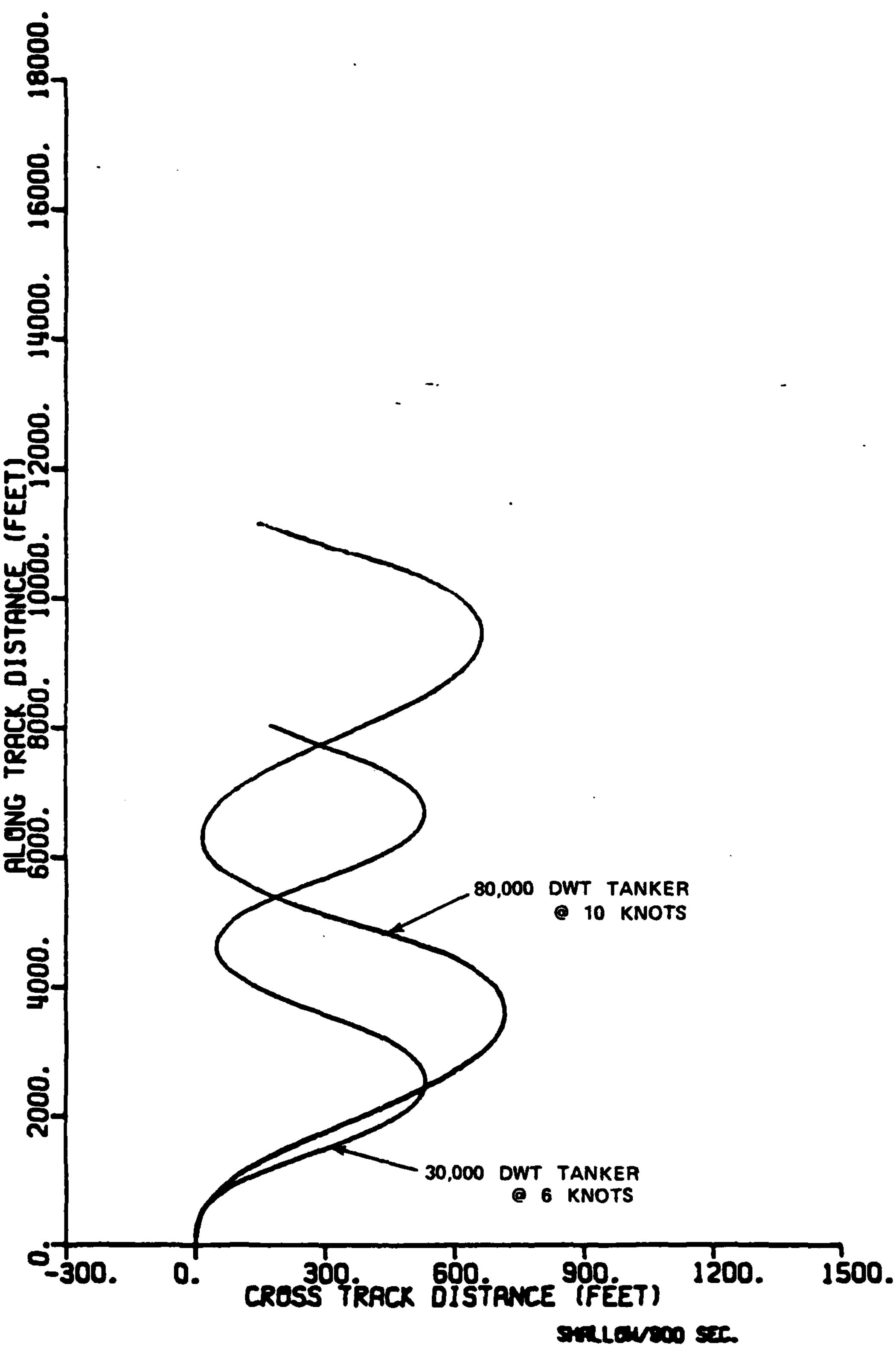

ALONG TRACK DISTANCE (FEET)
0.
2000.
4000.
6000.
8000.
10000.
12000.
14000.
16000.
18000.
-300.
0.
300.
600.
900.
1200.
1500.
CROSS TRACK DISTANCE (FEET)
80,000 DWT TANKER
@ 10 KNOTS
30,000 DWT TANKER
@ 6 KNOTS
SHALLOW/800 SEC.

Figure B-14

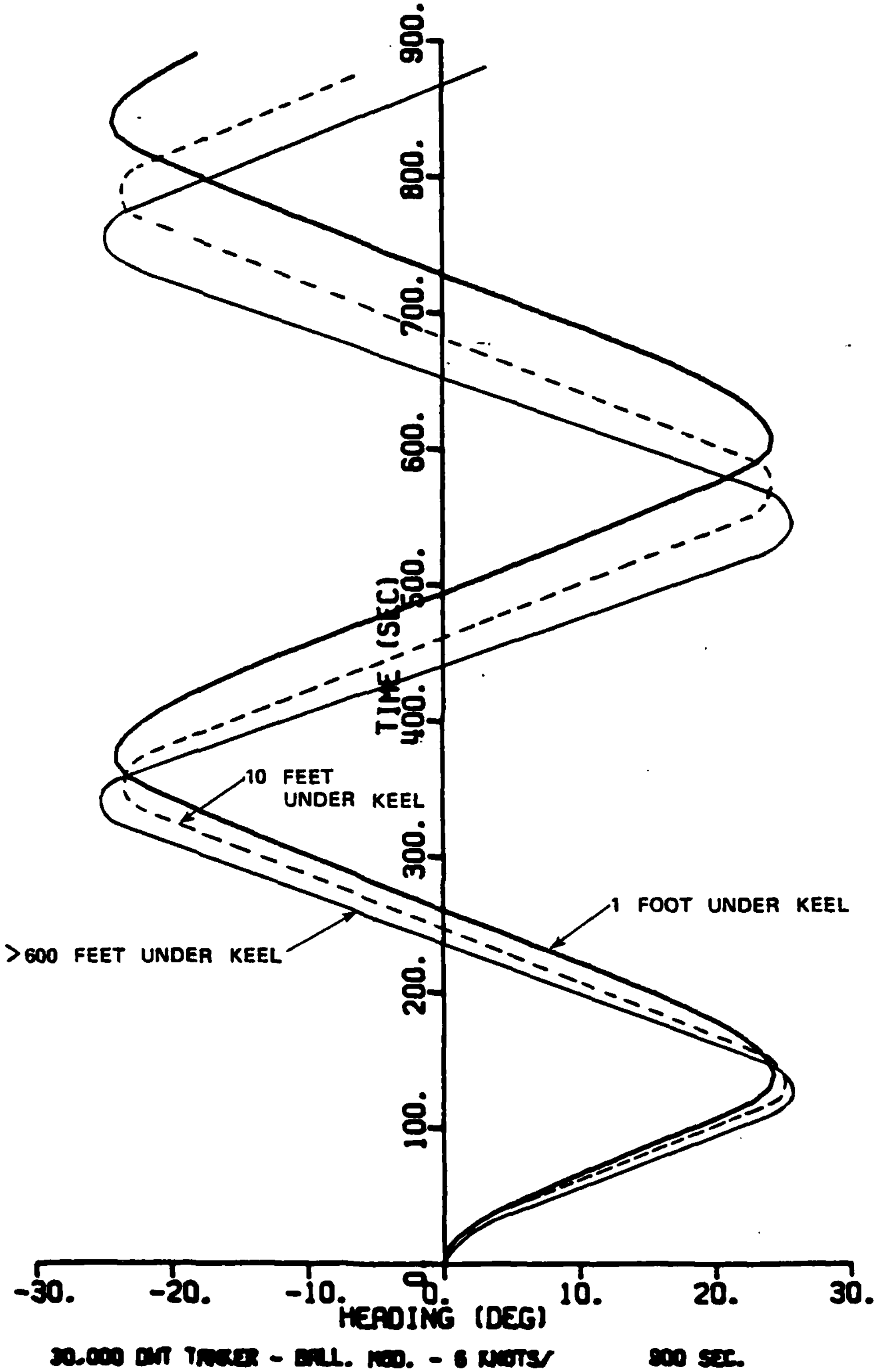

900.
800.
700.
600.
500.
400.
300.
200.
100.
0.
TIME (SEC)
10 FEET UNDER KEEL
1 FOOT UNDER KEEL
>600 FEET UNDER KEEL
-30.
-20.
-10.
0.
10.
20.
30.
HEADING (DEG)
30.000 DWT TANKER - BALL. MOD. - 6 KNOTS/ 900 SEC.

Figure B-15

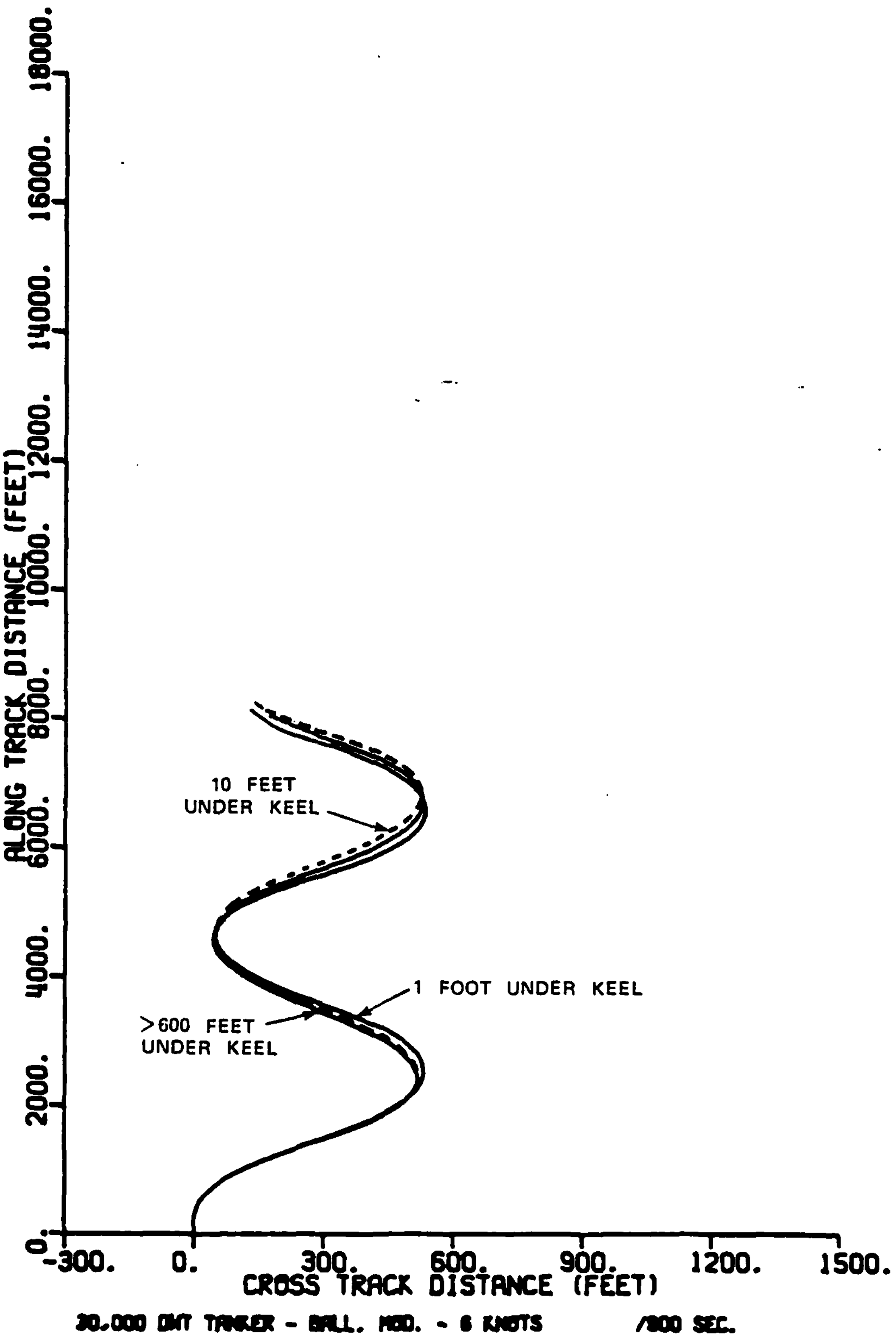

ALONG TRACK DISTANCE (FEET)
0.
2000.
4000.
6000.
8000.
10000.
12000.
14000.
16000.
18000.
-300.
0.
300.
600.
900.
1200.
1500.
CROSS TRACK DISTANCE (FEET)
10 FEET UNDER KEEL
1 FOOT UNDER KEEL
>600 FEET UNDER KEEL
30,000 DWT TANKER - BALL. MOD. - 6 KNOTS /800 SEC.

Figure B-16

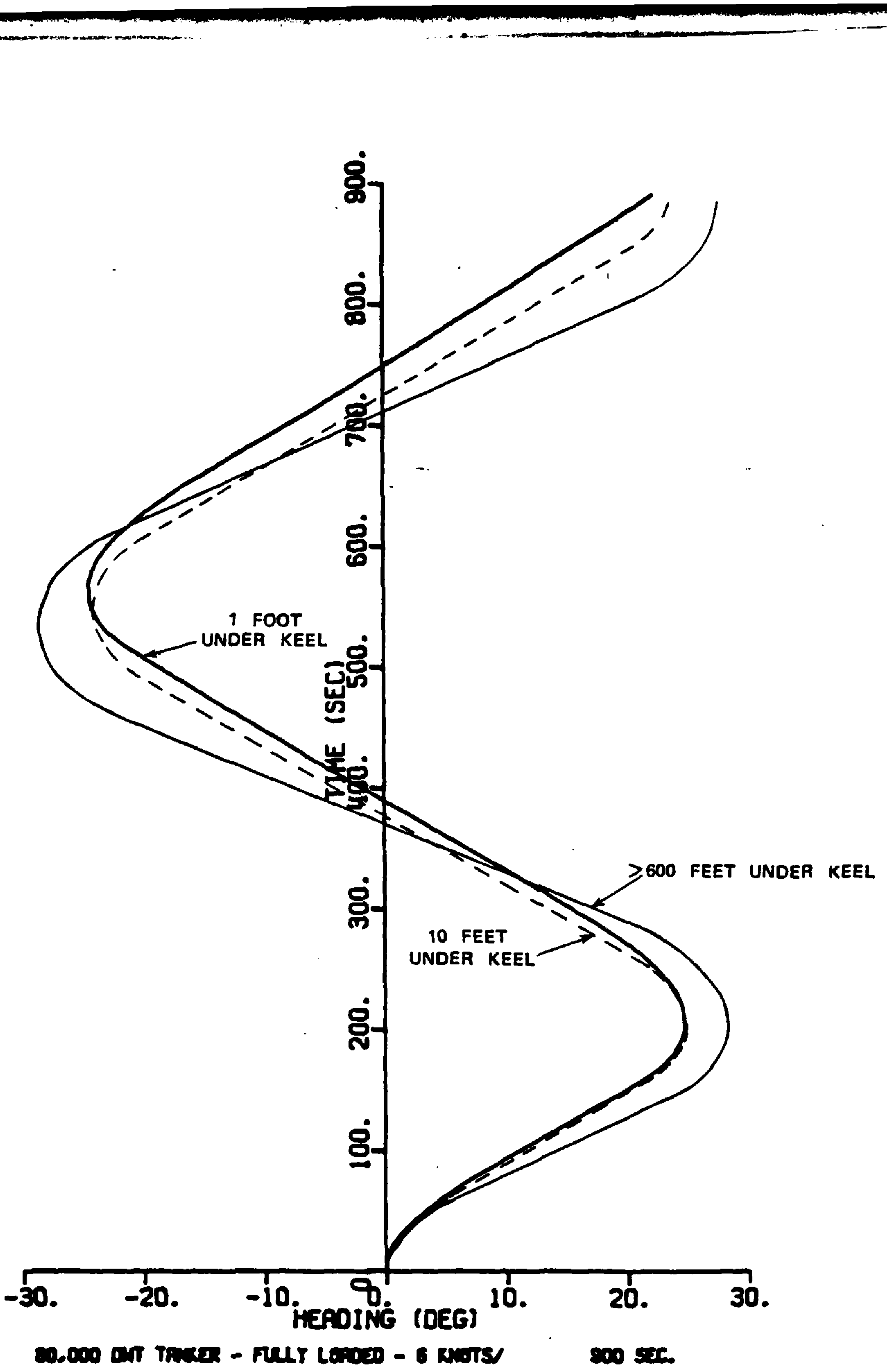
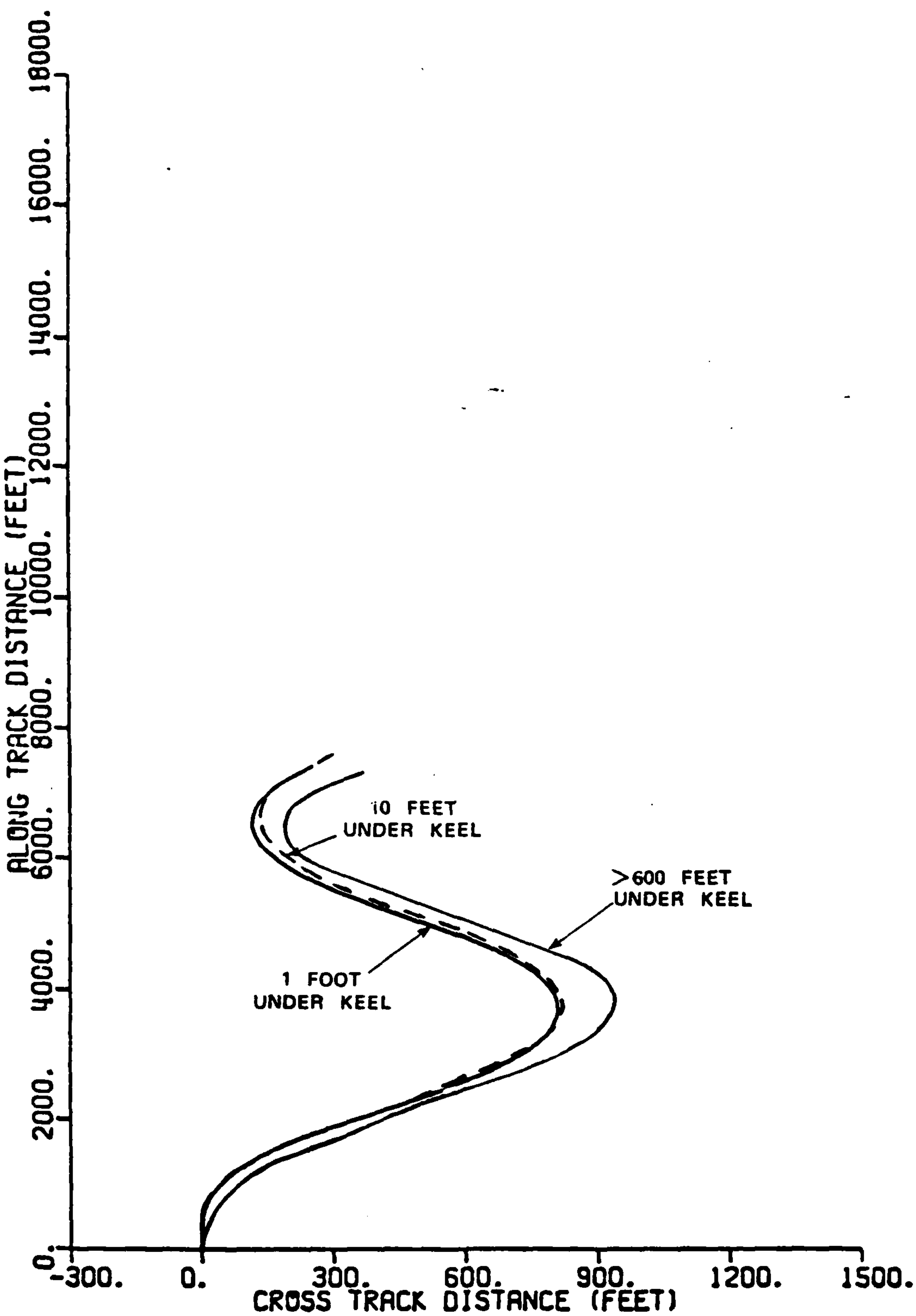

900.
800.
700.
600.
500.
400.
300.
200.
100.
TIME (SEC)
1 FOOT
UNDER KEEL
>600 FEET UNDER KEEL
10 FEET
UNDER KEEL
-30.
-20.
-10.
0.
10.
20.
30.
HEADING (DEG)
80,000 DWT TANKER - FULLY LOADED - 6 KNOTS/ 900 SEC.

Figure B-17



80,000 DWT TANKER - FULLY LOADED - 6 KNOTS/ 900 SEC.

Figure B-18

APPENDIX C

WIND AND CURRENT VARIATIONS

C.1 INTRODUCTION

The wind and current variations are the same that were used in the Ship Variables experiment. (In the presimulation report for that experiment, they are compared to the effects in the Channel Width and CAORF experiments.) Both parameters are time varying functions which produce difficult (but realistic) piloting and steering tasks.

C.2 CURRENT

The current direction is constant throughout the one-side experiment. The magnitude of the current, however, decreases with elapsed simulation run time such that the current reaches 0 knots near the end of the scenario. The current direction and magnitude functions are listed below. A plot of current magnitude versus time is shown in Figure C-1.

Current Direction

$$TWC = 341 \text{ (degrees)}$$

Current flows towards this bearing.

Current Magnitude (calculated for four points (I) along the hull)

$$RVWC\ (I) = VWC\ (I) \text{ cosine } (TMULT)\ (T1MAIN + TADD)\ (\pi/180))$$

where:

VWC(I) = 2.5317 feet/second (1.5 knots)

TMULT = 2

T1MAIN = elapsed run time (minutes)

TADD = 10.48 (minutes) = initial offset time

C.3 WIND

The wind direction and speed are both time varying. The wind functions for the one-side experiment are listed below. A plot of the magnitude function is shown in Figure C-2. A plot of the direction function is shown in Figure C-3.

Wind Speed

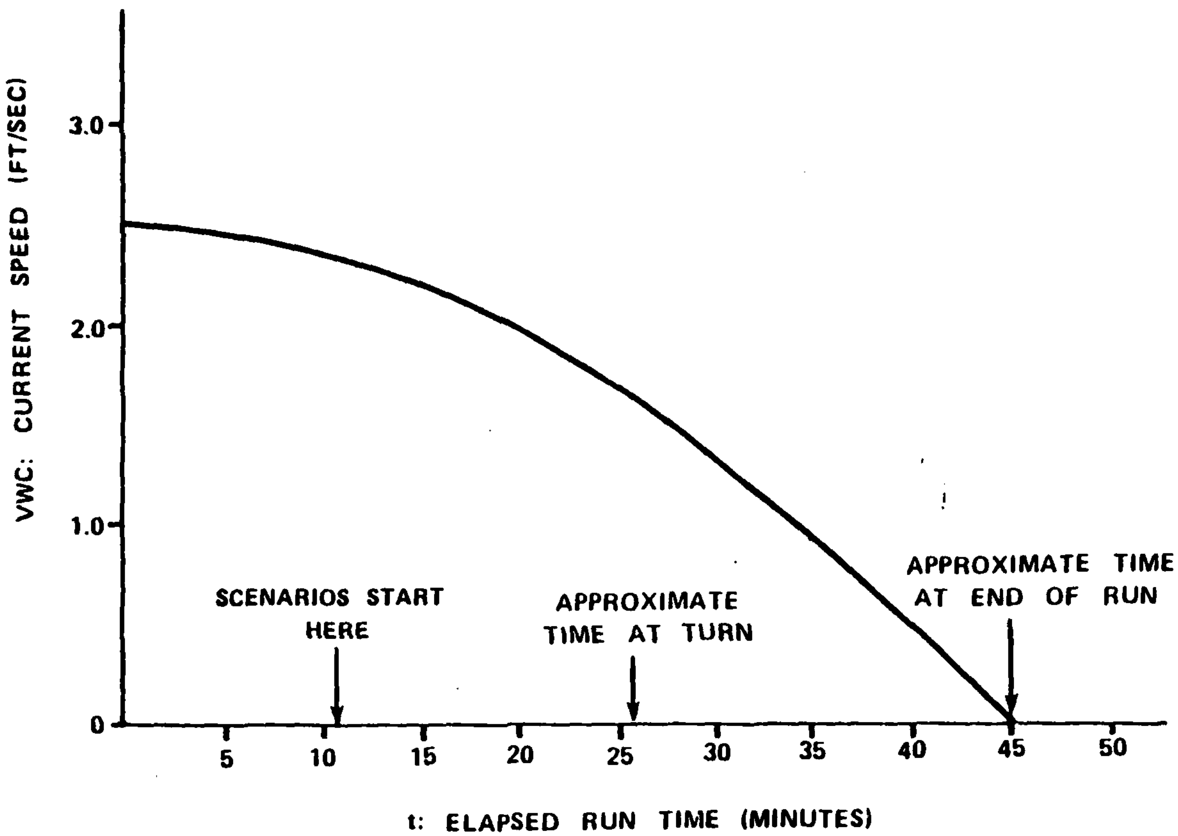
$$RWWS = WWS + (0.0019)\ (T1MAIN + TADD - 10.48)\ (WWS)$$
$$+ (0.02)\ (WWS) \text{ sine } (T1MAIN + TADD - 10.48)\ 2\pi/3)$$

where:

WWS = 26.75 knots

TADD = 10.48 (minutes)

T1MAIN = elapsed run time (minutes)



VWC = 2.53 cos (t + to) ft/sec

Figure C-1. Current Speed Function

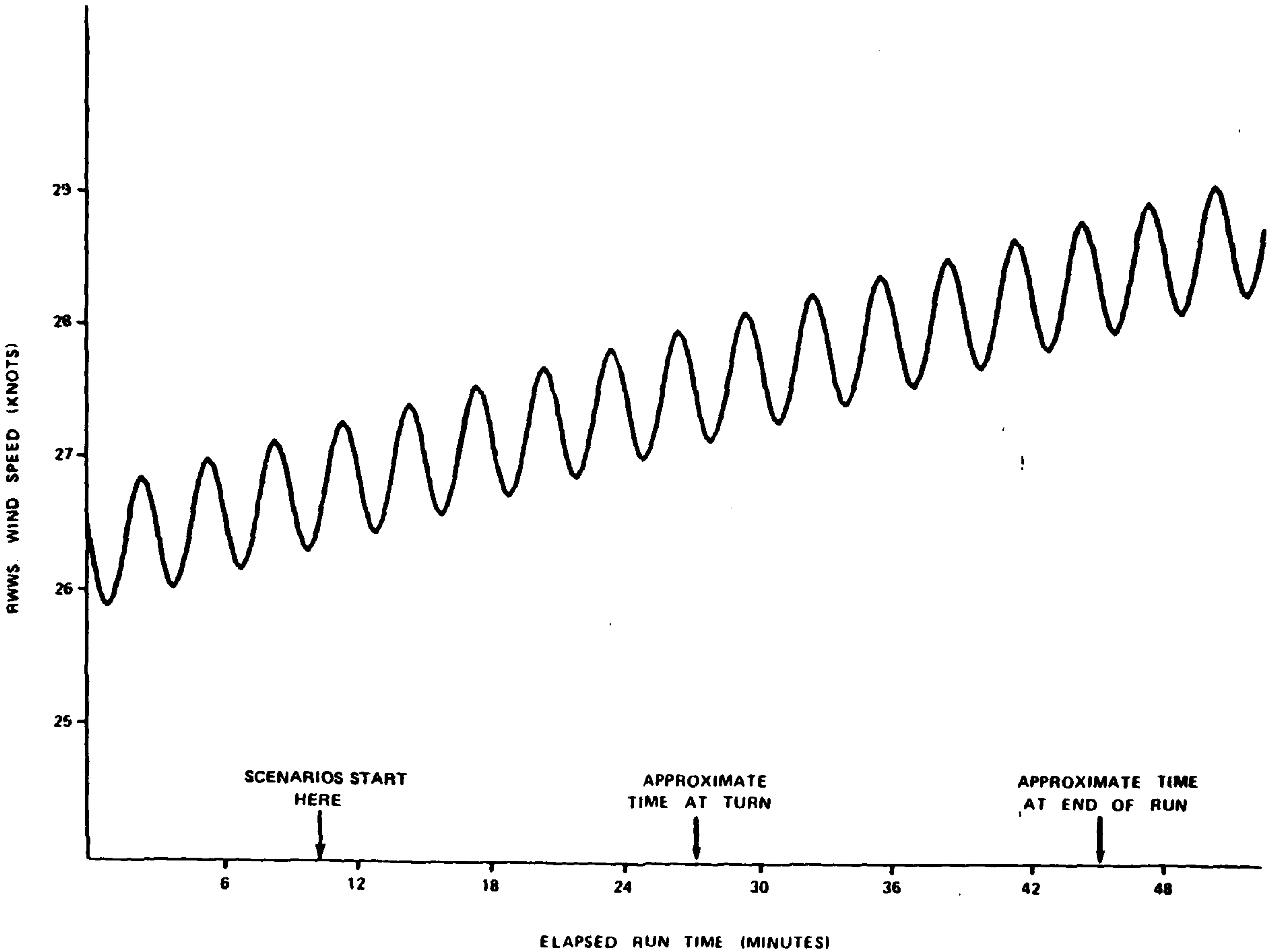


Figure C-2. Wind Speed Function

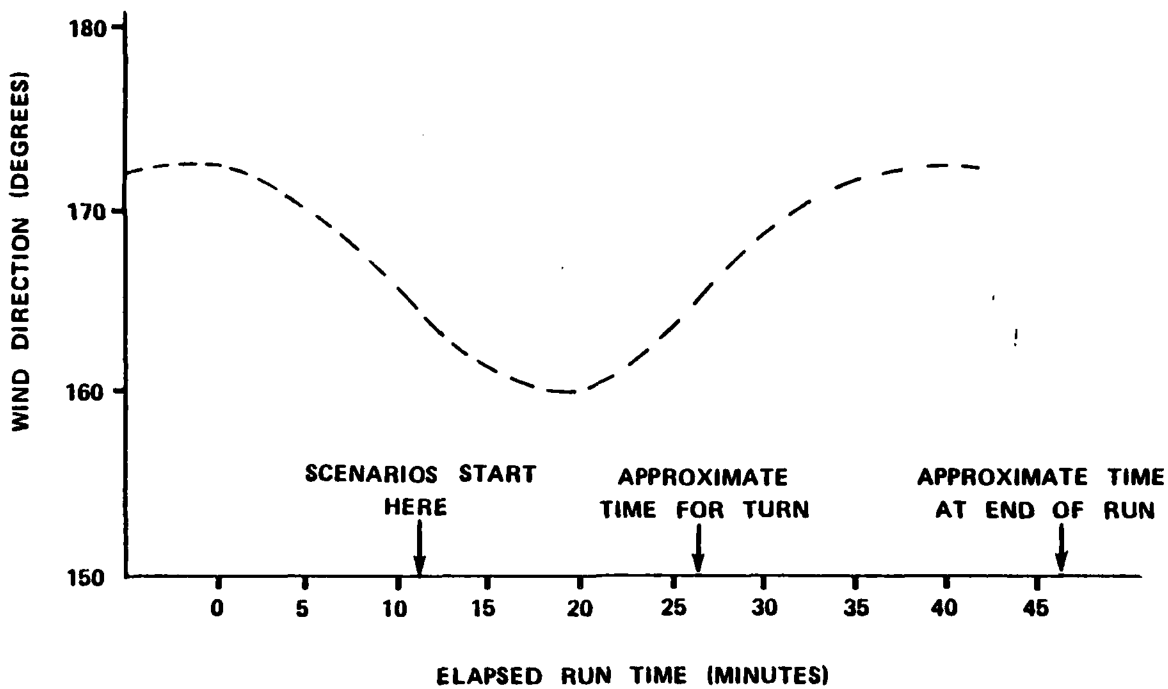


Figure C-3. Wind Direction Function

Wind Direction

$$RWWD = WWD + (6) \text{ cosine } ((T1MAIN + TADD - 6)\, 2\pi/36)$$

where:

WWD	= 166 degrees (direction from which wind blows)
T1MAIN	= elapsed run time (minutes)
TADD	= 10.48 (minutes)

APPENDIX D

SHIP VARIABLES EXPERIMENT: INSTRUCTIONS TO THE PILOT

INTRODUCTION

The purpose of this experiment is to demonstrate the effect of ship variables on piloting performance. The ships used today will vary in size (maneuverability and height of eye), location of the wheelhouse, speed, and bow image. A secondary purpose of the experiment is to examine the relationship between ship size and buoy density. For this purpose, the ship will be run in channels that differ in available buoy density.

There will be a total of eight scenarios today. The first will be meant to familiarize you with the wind and current. The others will be experimental scenarios, differing in the conditions named above. They will be 45 minutes long or less. At the end of the day, there will be a questionnaire to allow you to express your opinion on the conditions of the experiment.

CONDITIONS COMMON TO ALL SCENARIOS

a. Bridge conditions: There will be:

- a helmsman on the bridge to receive your orders
- a gyrocompass
- an engine order telegraph
- charts and a current diagram

b. Visual conditions: All experimental scenarios will be run under daytime conditions with a 1-1/2 nm visibility. You will see unlit 17-foot buoys in these daytime scenarios. It is important that you stay at the center of the bridge. It is only there that the buoys appear in the proper locations and perspective for the conditions.

c. The channel and environmental conditions: The general layout of the channel and current conditions are illustrated in Figure D-1. The scenarios contain a 500-foot wide channel, with the entrance marked by a sea buoy. The whole scenario has shallow water effects. There are no bank effects in the channel. The channel has a 35-degree turn to the left with no cutoff.

The current is 1.5 knots at 341°T at the approach to the sea buoy. It moves up the channel in its first leg, decreasing to 3/4-knot at the turn. There it is broad on the port quarter at the pullout. In the second leg, the current gradually turns to follow the channel again. It decreases in speed until it is zero knots when the scenario ends.

There is a gusting wind averaging 30 knots throughout the scenario. It maintains an average direction of 161°T throughout the run.

d. Initialization conditions: The ship will be initialized 2400 feet from the sea buoy on a course of 008°T. The sea buoy which is colored black and red in horizontal bands is located on the centerline of the channel. The channel course is 341°T.

e. Maneuvering instructions: Please enter the channel leaving the sea buoy to starboard. Once in the channel, move the ship to the centerline as quickly as you think prudent. Stay on the centerline trying to keep as strict a definition of "centerline" as is practical. You may leave the centerline when you decide it is necessary for the approach to the turn. Use your own strategy to negotiate the turn. In the second leg, return to the centerline as soon as possible and maintain it until the end of the run.

   The familiarization run will be shortened, beginning in the last gate below the turn and ending soon after the run.

f. Speed at initialization will be 6 or 10 knots through the water. The rpm varies with the ship and is indicated on the summary card for each scenario. Please maintain the set speed. You may change speed to negotiate the turn if you think it necessary. Please return to the initial speed as soon as possible in the second leg.

PERCEPTUAL MEASURES

a. There are arrangements for an extra measure of just how well the conditions allow you to judge the ship's position in the channel. There is a panel on the bridge with buttons for you to press to indicate the ship's position relative to the centerline. (See Figure D-2.) The buttons will light up about once a minute. Please press one to indicate whether the ship is to the right, on the centerline, or to the left of the centerline. When you press a button, hold it down until the light goes off. If you do not press it, it will go off in 30 seconds.

b. Please make these judgments as precise as possible. Define the position of the ship as the position of its center of gravity and define the centerline of the channel as narrowly as possible. (For the 80,000 dwt tanker with the rear wheelhouse, the eye point is behind the center of gravity.)

   Press the "CL" button only when you consider the center of gravity to be on the exact centerline. Press the "L" or "R" button when you consider it to be to the left or right of the centerline. It is not necessary to order a heading change because you indicated the ship is not on the exact centerline if you do not think it is practical to try to bring it closer to the centerline than it is. When the ship's center of gravity is not at the centerline because of maneuvering requirements, indicate its relationship to the centerline from wherever it is.

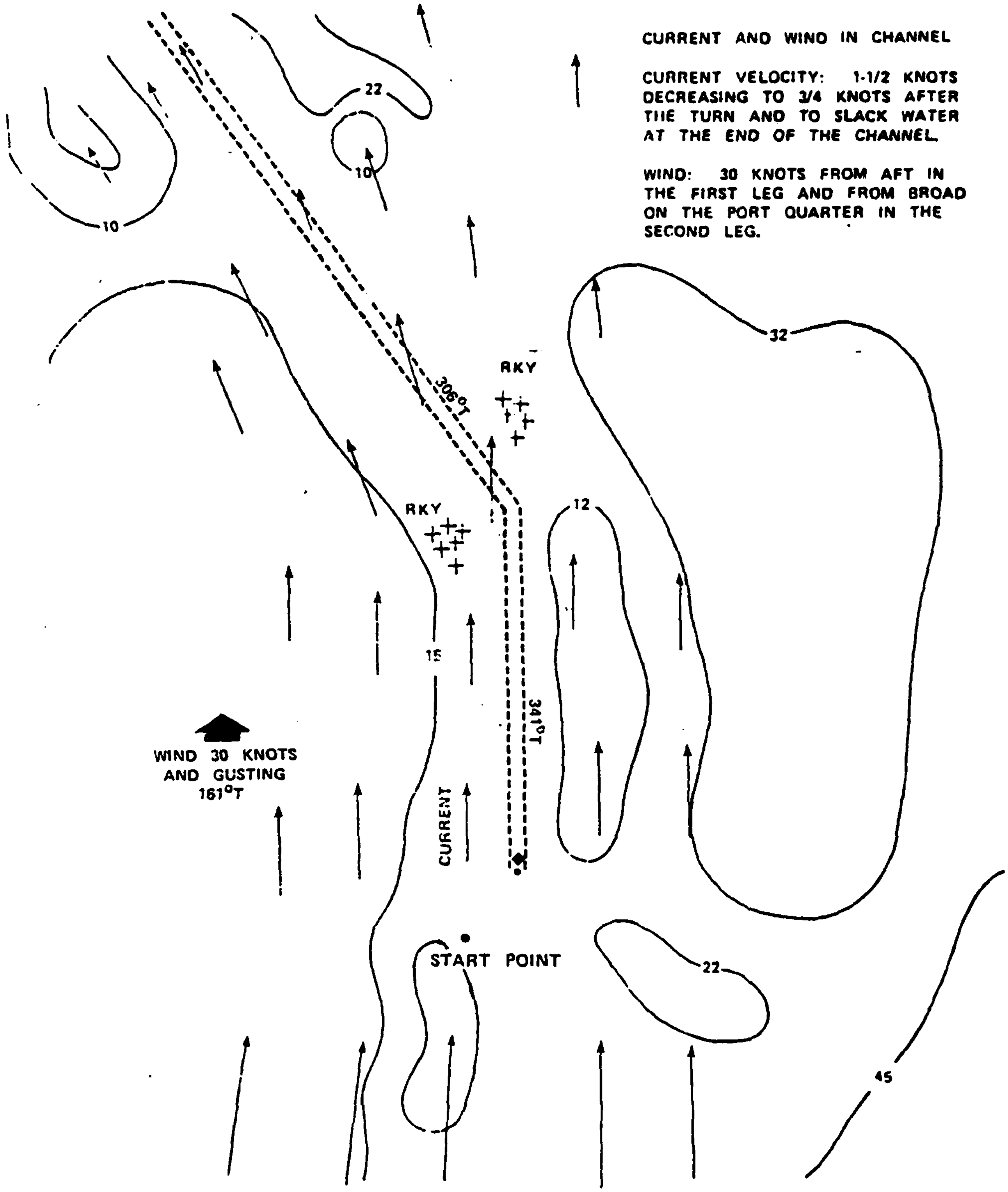
c. Please respond to the lights as frequently as possible, guessing if you think you have a chance of being correct. If you have no idea at all where the ship is and do not want to guess, do not press anything. The lights will go off in 30 seconds.

d. Please judge the ship's position as accurately as you can each time. Make each judgment independently of the one before. It is not necessary to be consistent from one response to the next.

Please feel free to ask questions or make comments at any time.

VARIABLE CONDITIONS

Cards will be provided summarizing the eight scenarios.



CURRENT AND WIND IN CHANNEL
CURRENT VELOCITY: 1-1/2 KNOTS DECREASING TO 3/4 KNOTS AFTER THE TURN AND TO SLACK WATER AT THE END OF THE CHANNEL.
WIND: 30 KNOTS FROM AFT IN THE FIRST LEG AND FROM BROAD ON THE PORT QUARTER IN THE SECOND LEG.
22
10
10
32
306°T
RKY
RKY
12
15
341°T
WIND 30 KNOTS AND GUSTING 161°T
CURRENT
START POINT
22
45

Figure D-1.

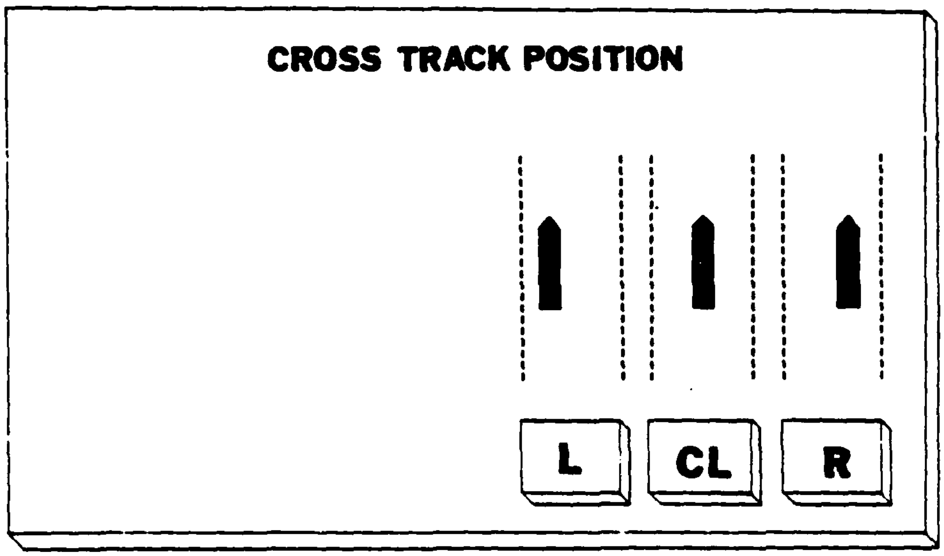


Figure D-2

SHIP VARIABLES EXPERIMENT: POSTSIMULATION QUESTIONNAIRE

1. Experimental variables and their effect on performance.

   1.1 Familiarization with the ship: Was the turn at the sea buoy at the beginning of each run adequate and appropriate to familiarize you with the handling and other characteristics of the ship? Would you have wanted more or different familiarization opportunities?

   1.2 The bow image: The 30,000 dwt tanker was simulated with a larger and smaller bow image. Which did you find more realistic? Did the difference have any effect on your piloting?

   1.3 Speed: The 80,000 dwt and the 30,000 dwt tanker were run at 6 and 10 knots. Which did you think was more appropriate for the conditions? Did you find the difference in ships' responses realistic? Did the differences influence your piloting?

1.4 Ship's size: Both a 30,000 dwt tanker and an 80,000 dwt tanker were used. Did you find the simulation of both realistic? Were the time for the rudder angle indicator to respond, the time for the ship to respond, rate of turn, and the time to check the swing realistic? Did the difference in handling characteristics for the two ships influence your piloting?

The two ships also differed in height of eye, 80 feet for the 80,000 dwt tanker and 45 feet for the 30,000 dwt tanker. Did you find the view realistic for the two ships? Did the difference influence your piloting?

1.5 AN placement and ship size: Did you find the piloting problem different when there were more or fewer buoys? Were you more or less dependent on the buoys with the different ship sizes?

2. Constant conditions and their effect on piloting.

2.1 Visual conditions: Were the buoys in proper perspective from the ship in proper relationships to the "horizon" line? Were they right for the visibility and spacing? Did the visual conditions have any effect on piloting that you would like to describe?

2.2 Current and wind effects: Were the current and wind effects realistic and as described in the instructions? How did they affect your piloting?

Was the familiarization scenario at the beginning of the day adequate and appropriate to familiarize you with the current and wind? Would you have wanted more or different familiarization opportunities?

2.3 Instructions to keep the ship on the centerline: Were the instructions to keep the ship on the centerline, except when necessary to leave it to maneuver realistic? What would you have preferred to do? Would the size of the ship or any other factor have influenced your preference?

2.4 Instructions to stand at the center of the bridge: Were the instructions to stand at the center of the bridge realistic? How did that affect your piloting?

2.5 <u>Lack of radar</u>: Was the lack of radar realistic for the conditions? Would you have used radar? How frequently would you use it and for what purpose?

3. The use of the bow image in piloting.

3.1 Did you use the bow image and window mullions as reference points for judging the position and movement of the buoys as they went by? Can you describe how you did this?

3.2 Were you influenced in this by factors that affected the bow image: ship size, height of eye, location of wheelhouse, size of bow image?

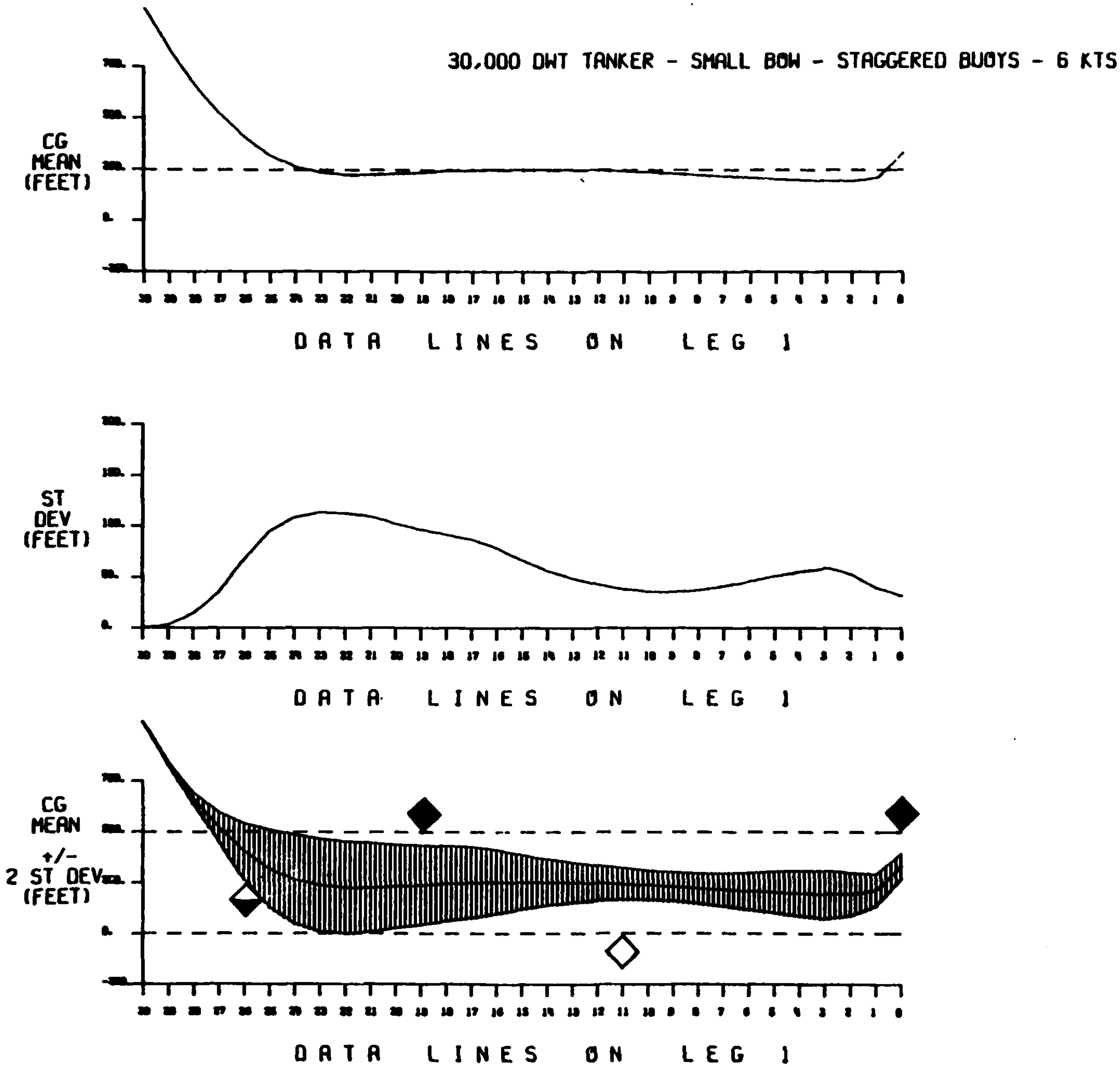
3.3 Were you influenced in this by the ship's speed or handling characteristics?

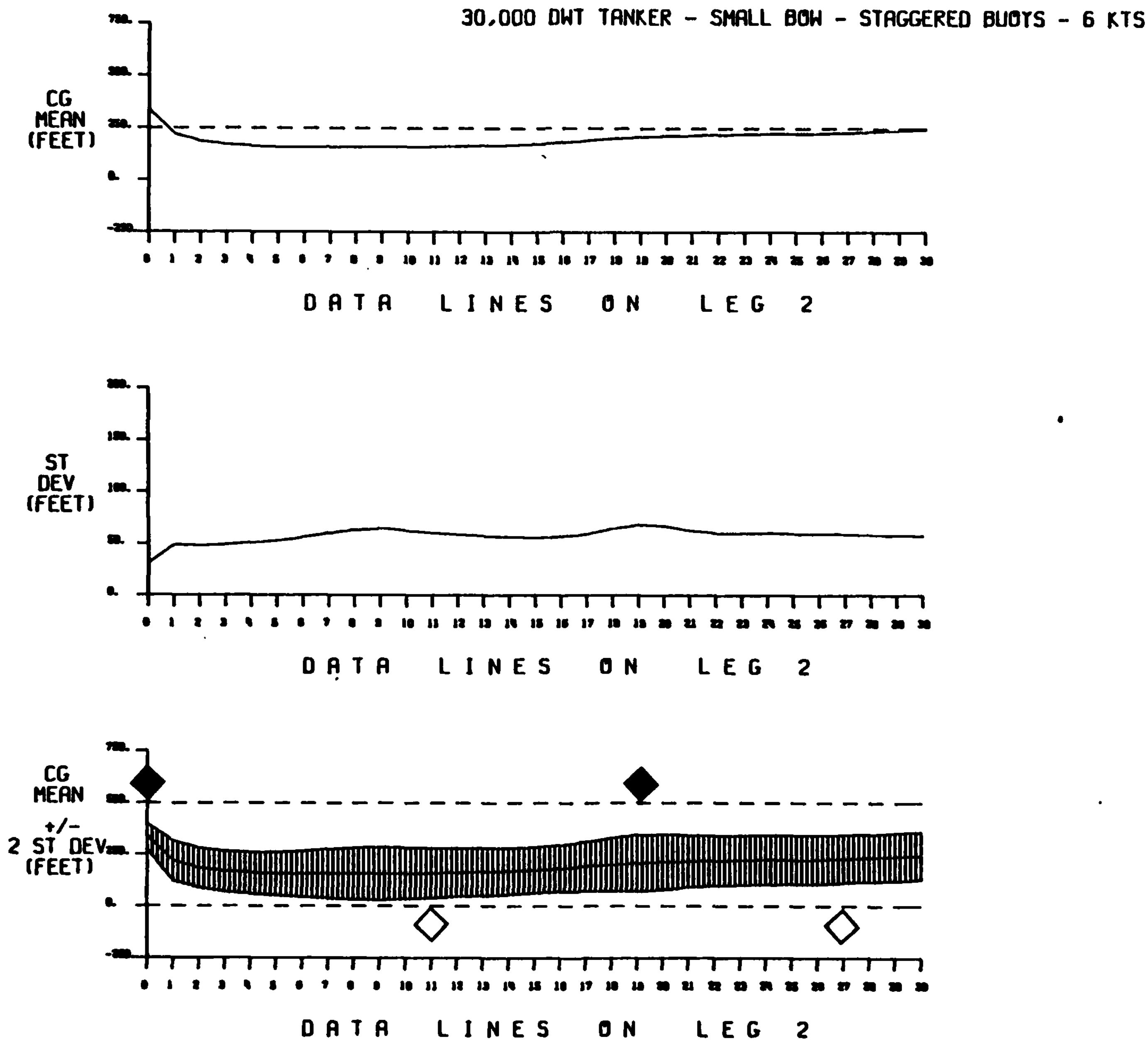
3.4 Were you influenced in this by the difference between the short-spaced, gated buoys and the long-spaced, staggered buoys?

APPENDIX E
PERFORMANCE DATA

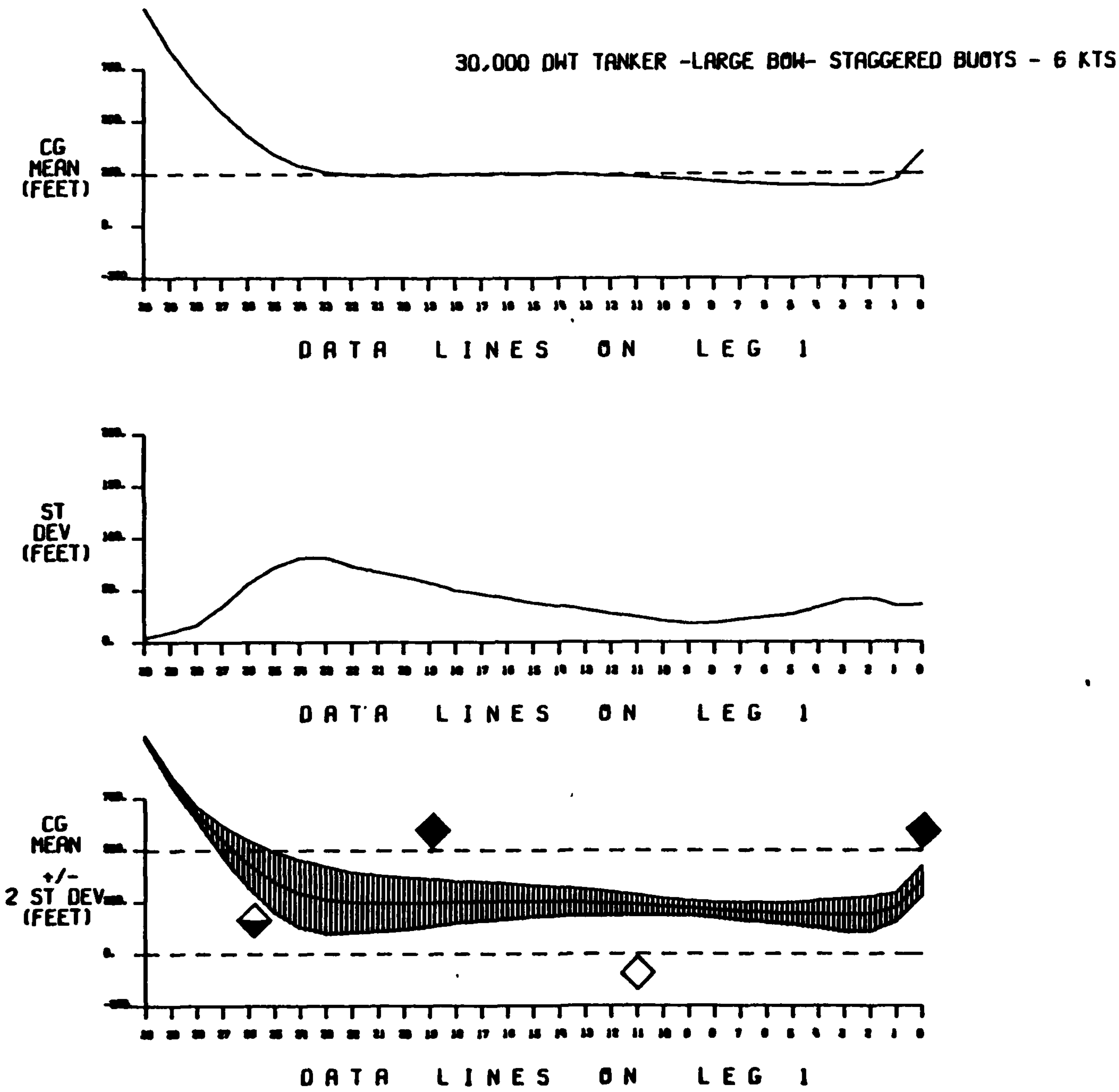
The following is a complete set of the plotted performance data from which the preceding report was written. The collection and analysis of this data is described in Section 1.4 in the main text.

- Individual Scenarios. Pages E-1 to E-14 are the individual scenarios outlined in Figure 1 on page 4 of the main text.
- Comparisons. Pages E-14 to E-34 are the individual scenarios compared in sets of two as outlined in Table 2 on page 3 of the main text.
- Turns. Pages E-35 to E-41 are plots of the individual scenarios through the turn.

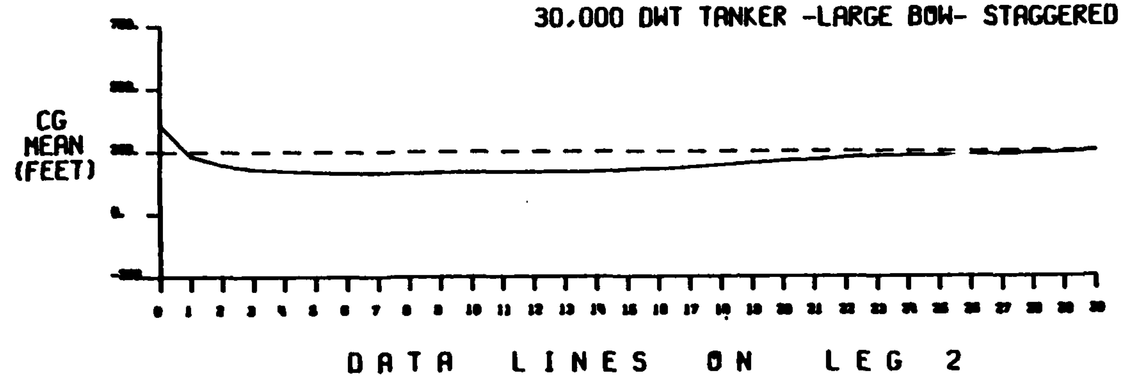

30,000 DWT TANKER - SMALL BOW - STAGGERED BUOYS - 6 KTS
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 1

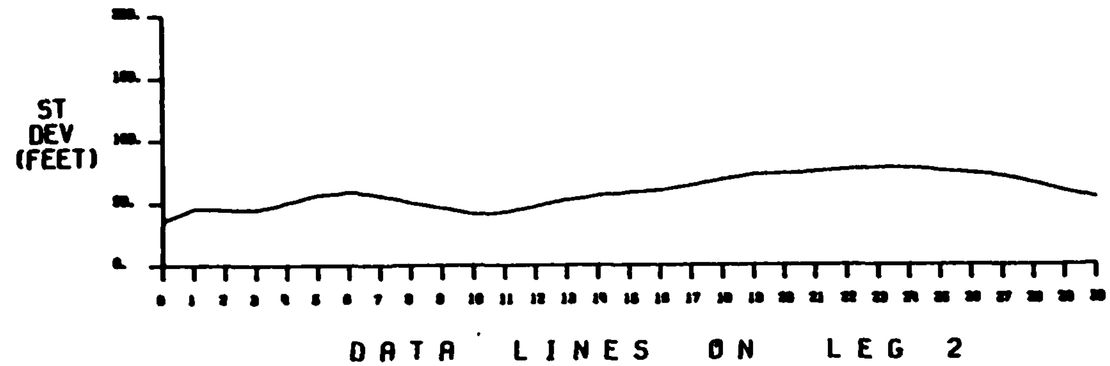

30,000 DWT TANKER - SMALL BOW - STAGGERED BUOYS - 6 KTS
CG
MEAN
(FEET)
DATA LINES ON LEG 2
ST
DEV
(FEET)
DATA LINES ON LEG 2
CG
MEAN
+/-
2 ST DEV
(FEET)
DATA LINES ON LEG 2

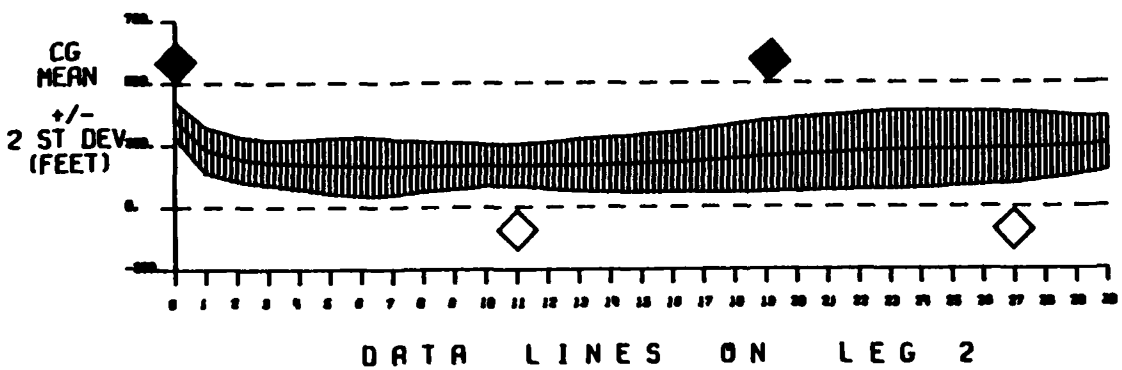
30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 6 KTS



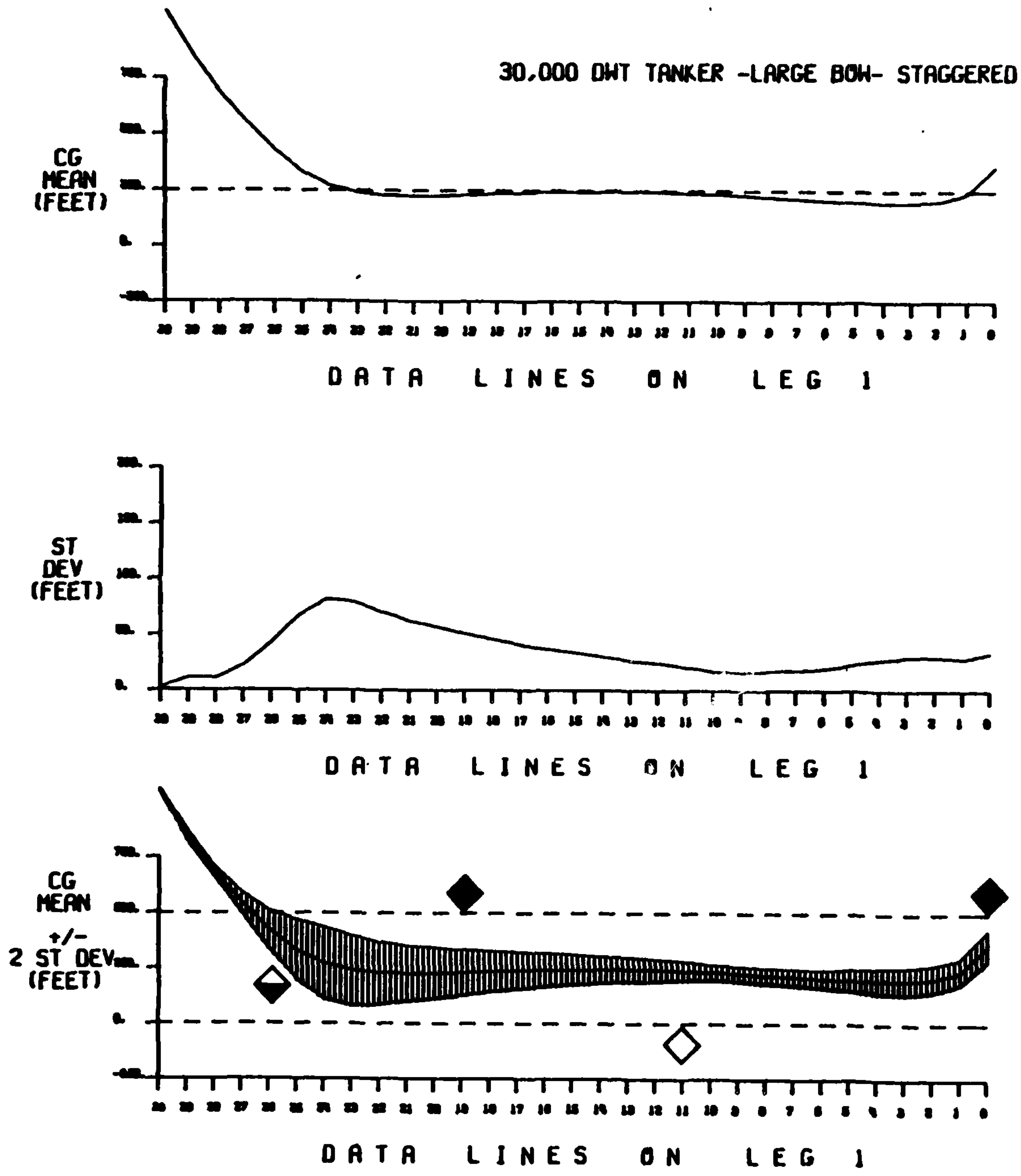
30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 6 KTS



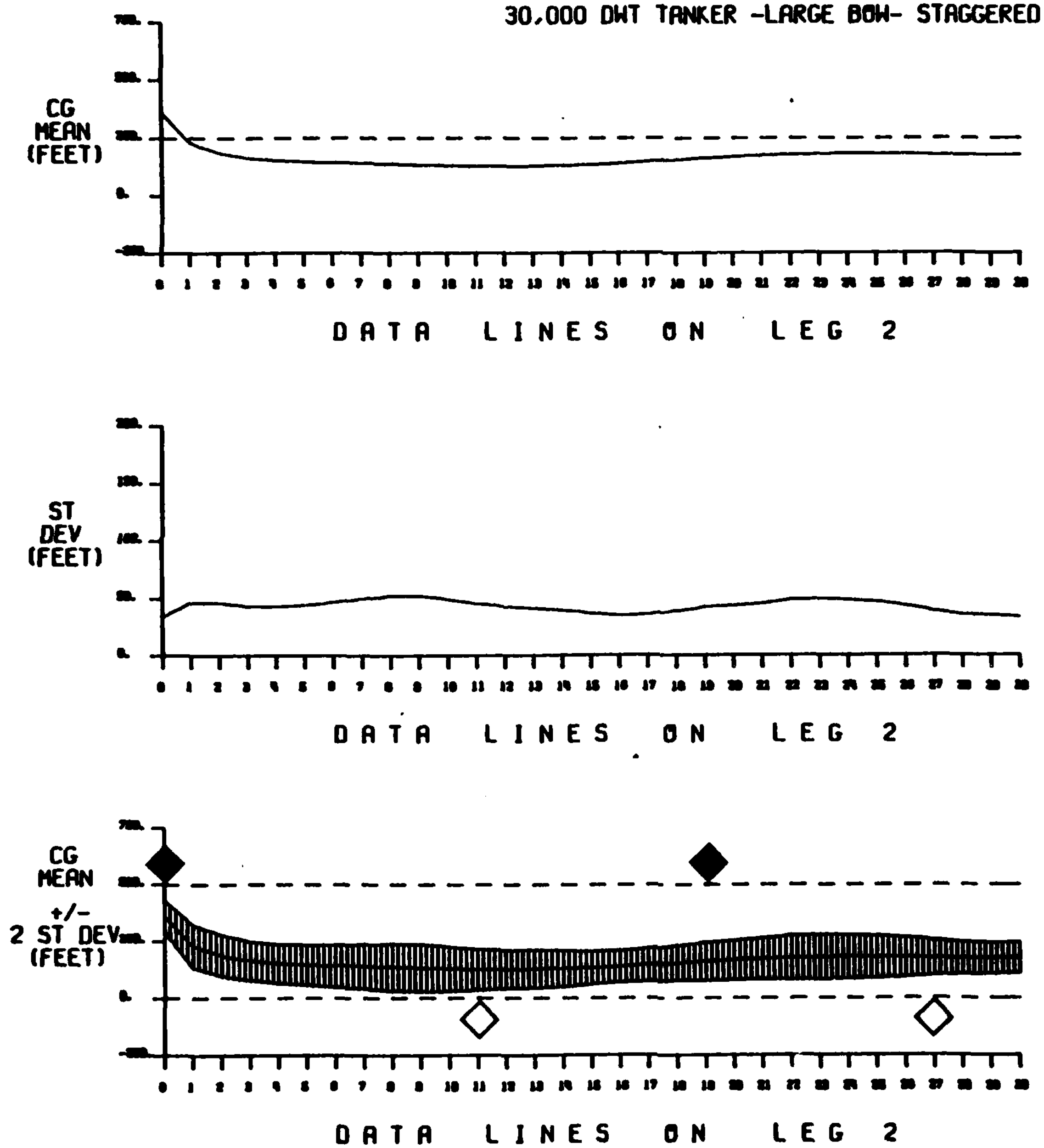


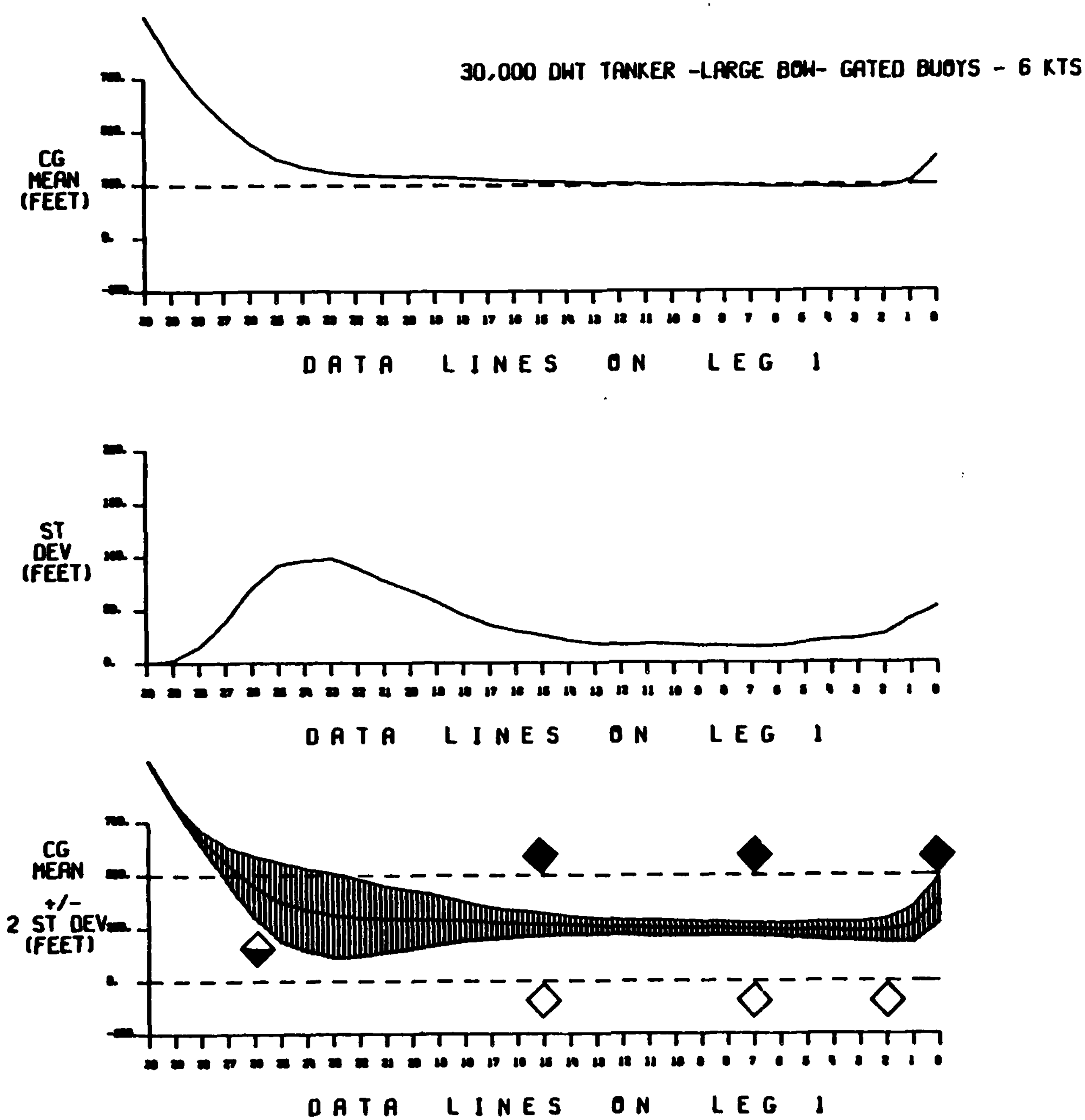


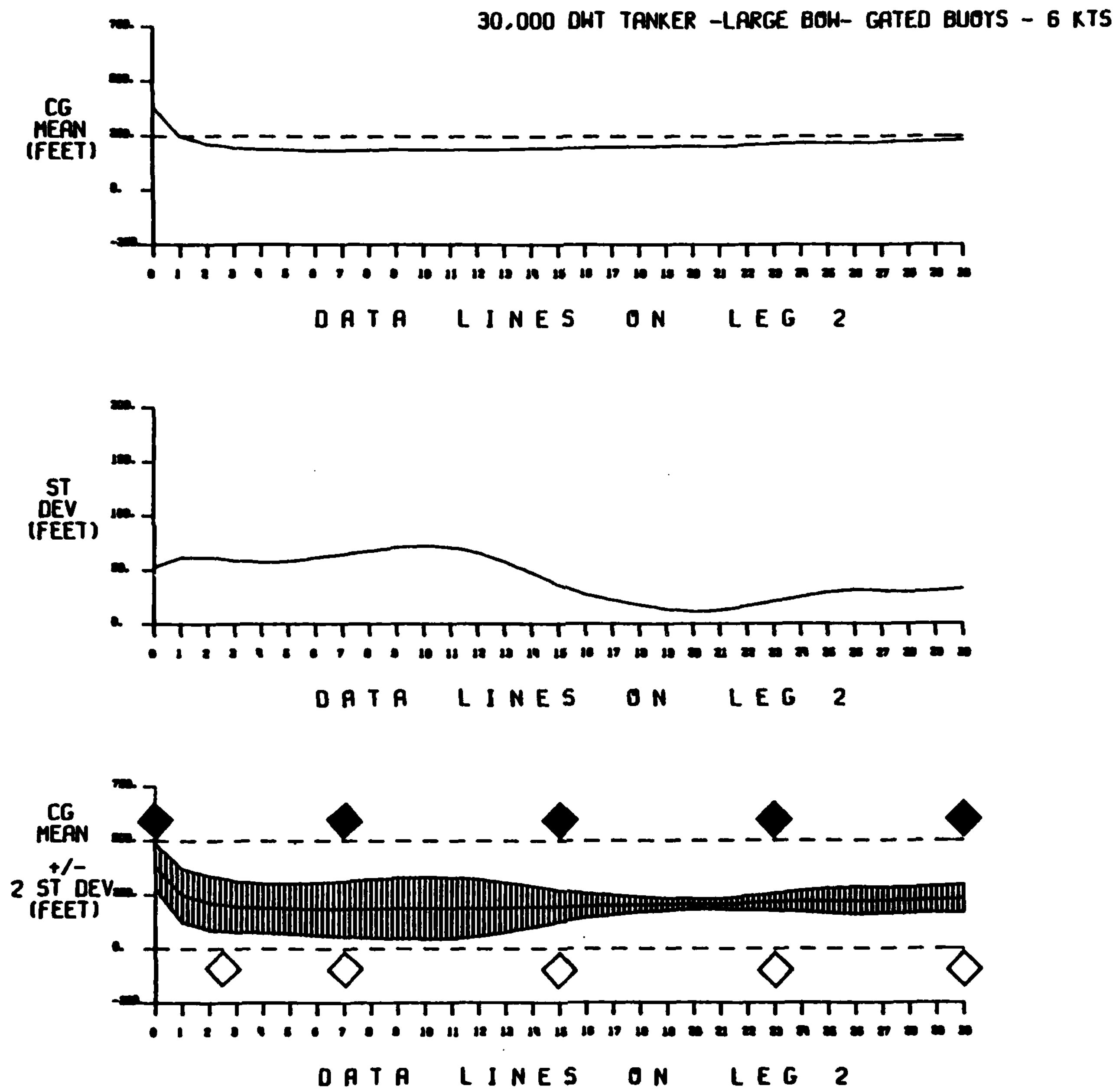
30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 10 KTS



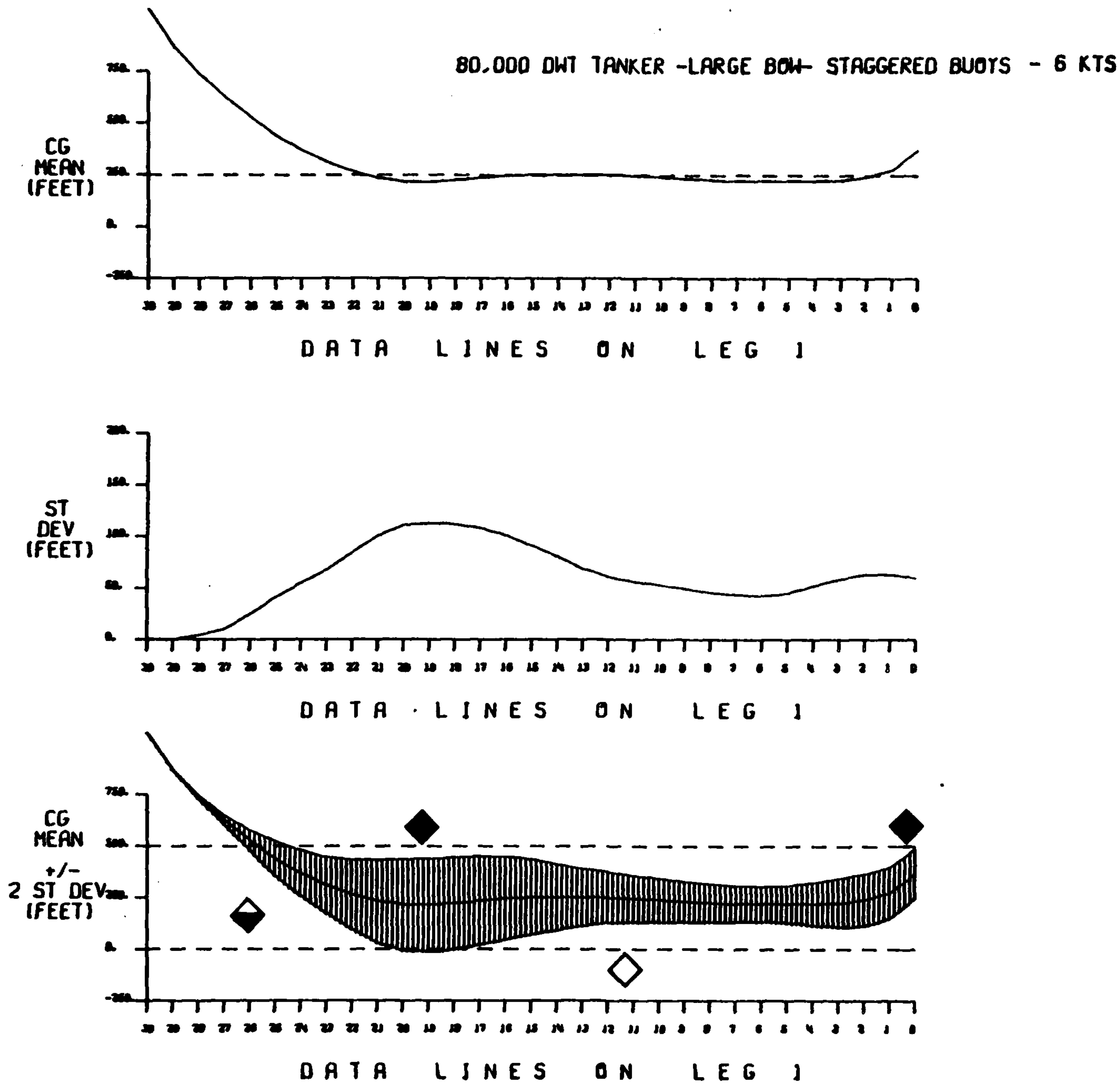
30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 10 KTS



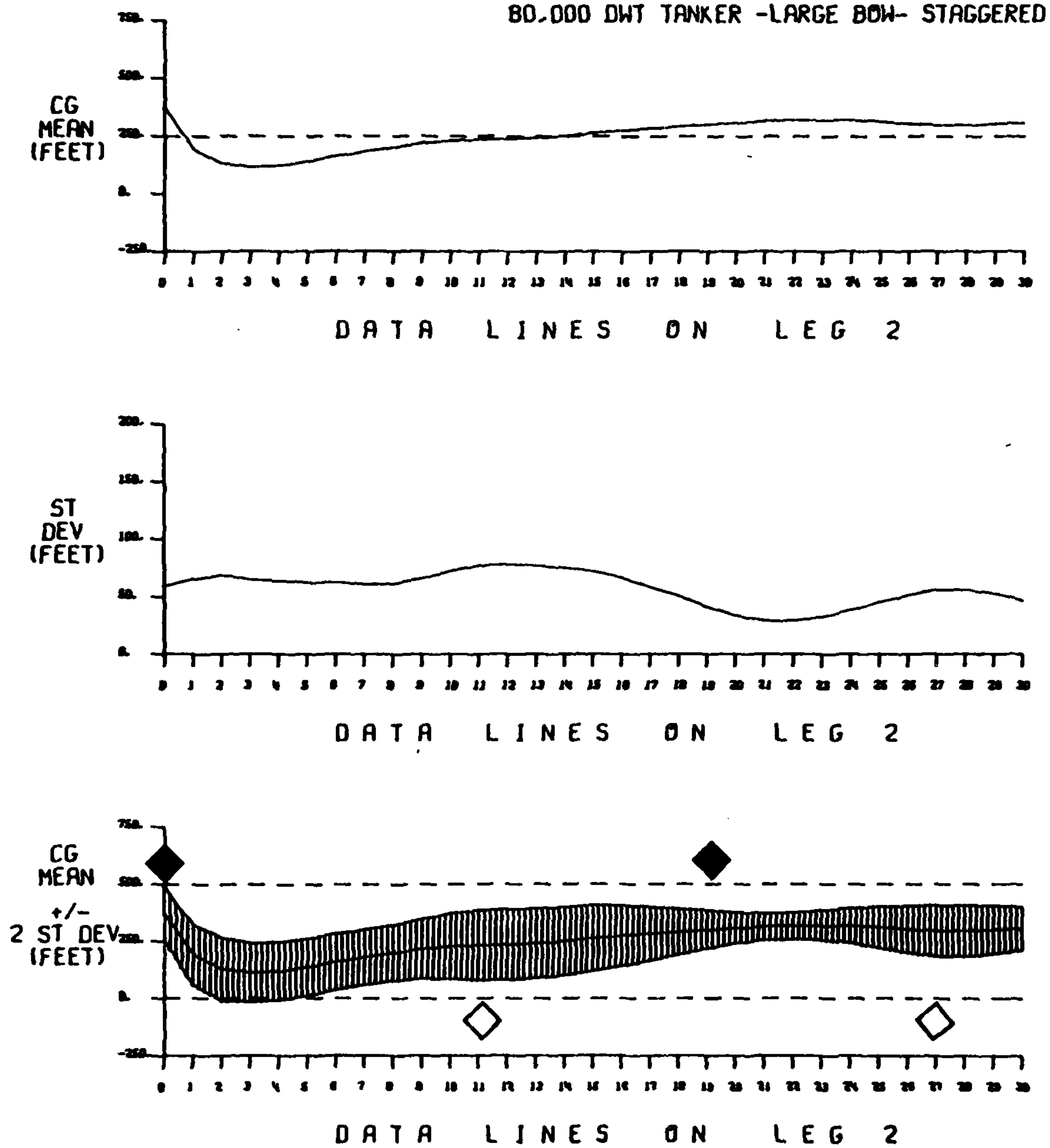

30,000 DWT TANKER -LARGE BOW- GATED BUOYS - 6 KTS
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 1



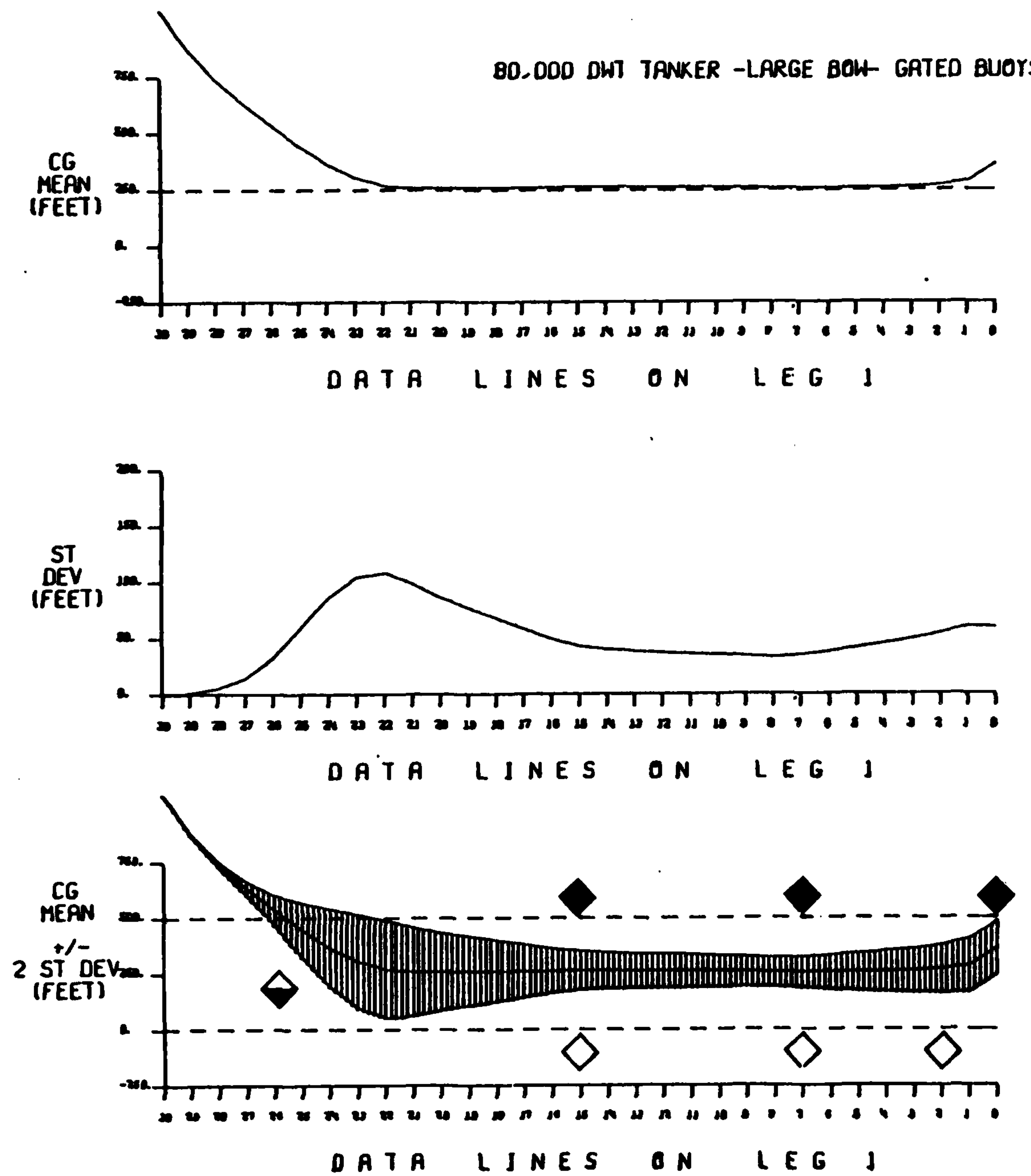
30,000 DWT TANKER -LARGE BOW- GATED BUOYS - 6 KTS
CG
MEAN
(FEET)
DATA LINES ON LEG 2
ST
DEV
(FEET)
DATA LINES ON LEG 2
CG
MEAN
+/-
2 ST DEV
(FEET)
DATA LINES ON LEG 2

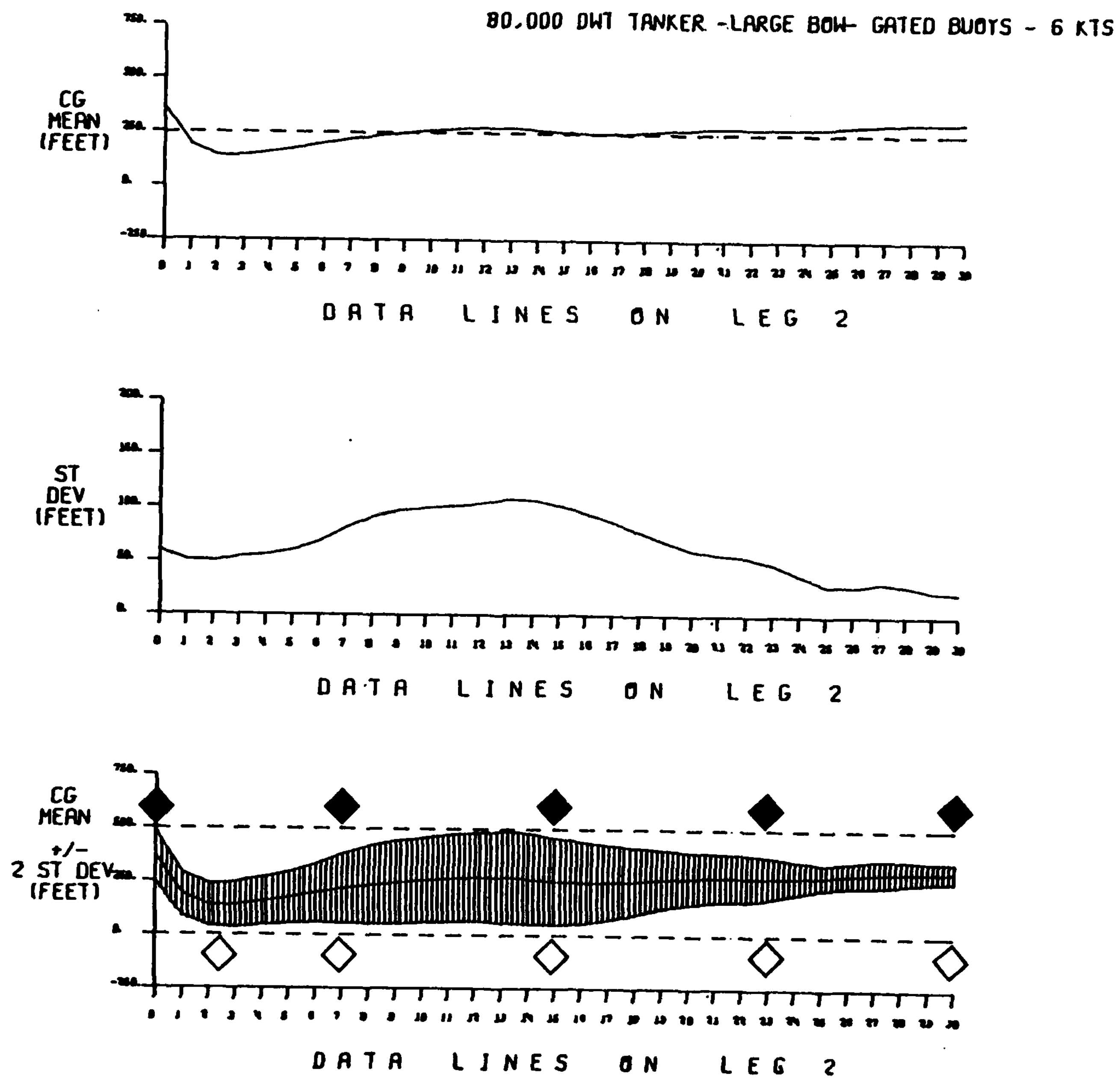

80,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 6 KTS
CG MEAN (FEET)
ST DEV (FEET)
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 1
DATA LINES ON LEG 1
DATA LINES ON LEG 1

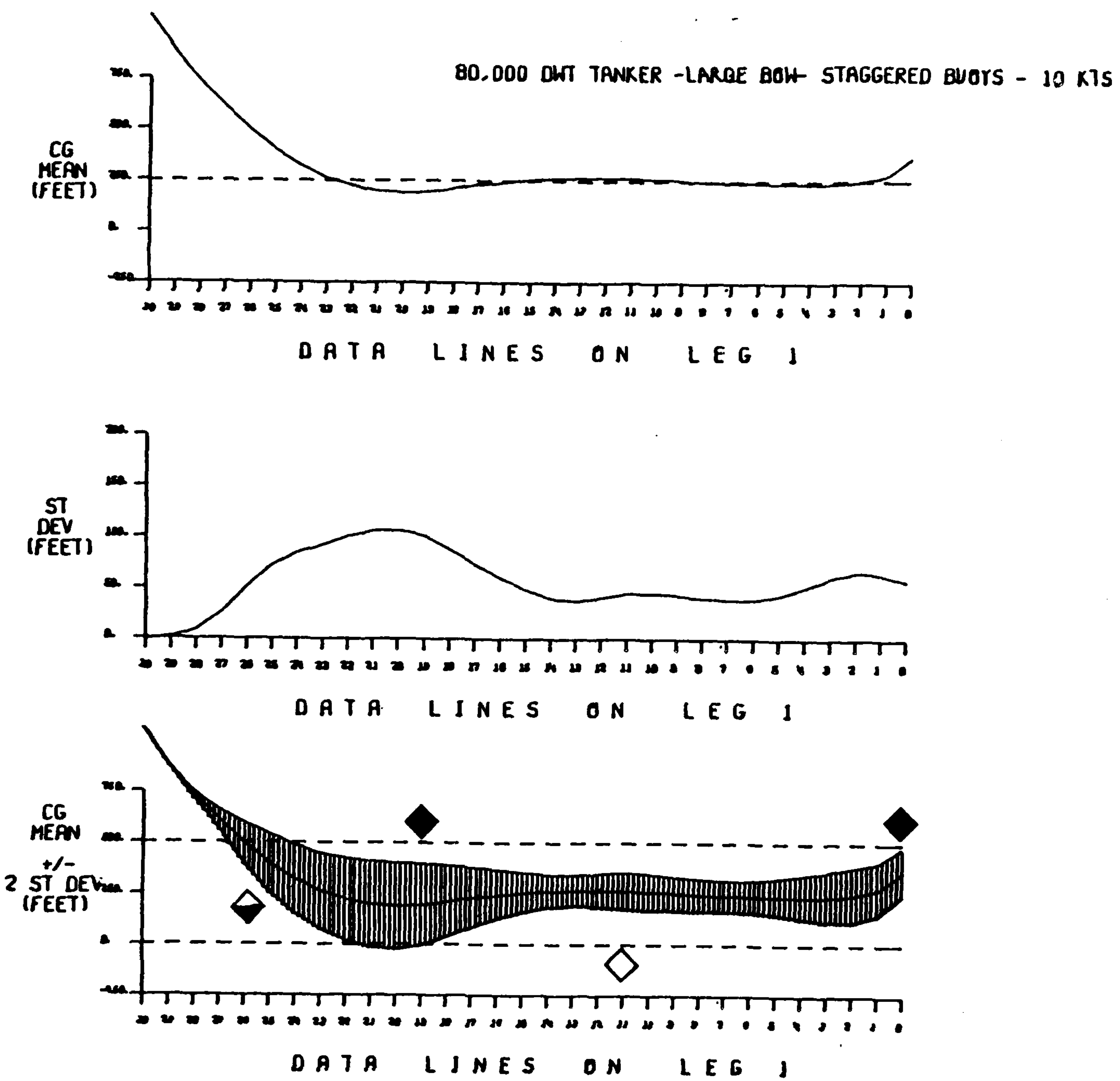
80,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 6 KTS



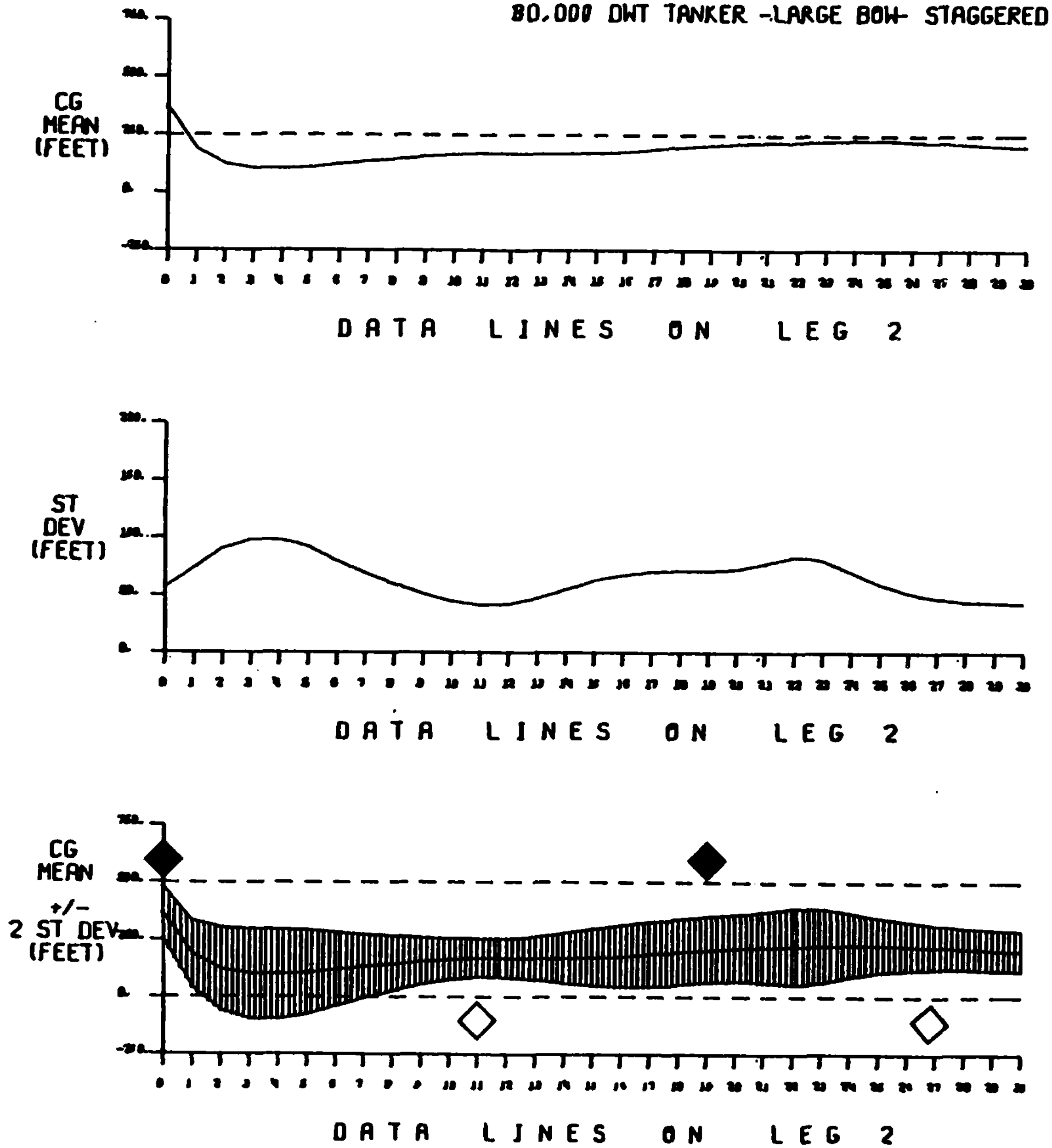
80,000 DWT TANKER -LARGE BOW- GATED BUOYS - 6 KTS

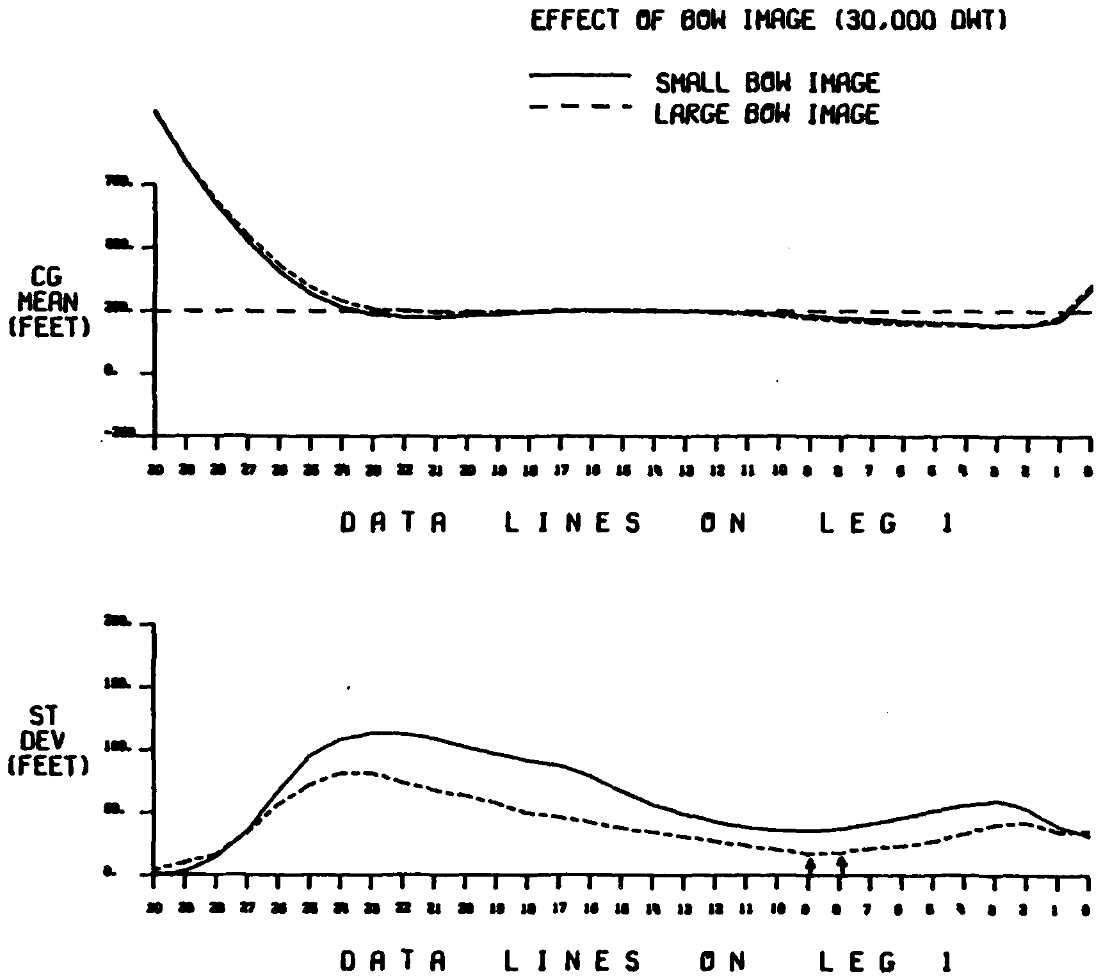



80,000 DWT TANKER -LARGE BOW- GATED BUOYS - 6 KTS
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2
CG MEAN +/- 2 ST DEV (FEET)
DATA LINES ON LEG 2

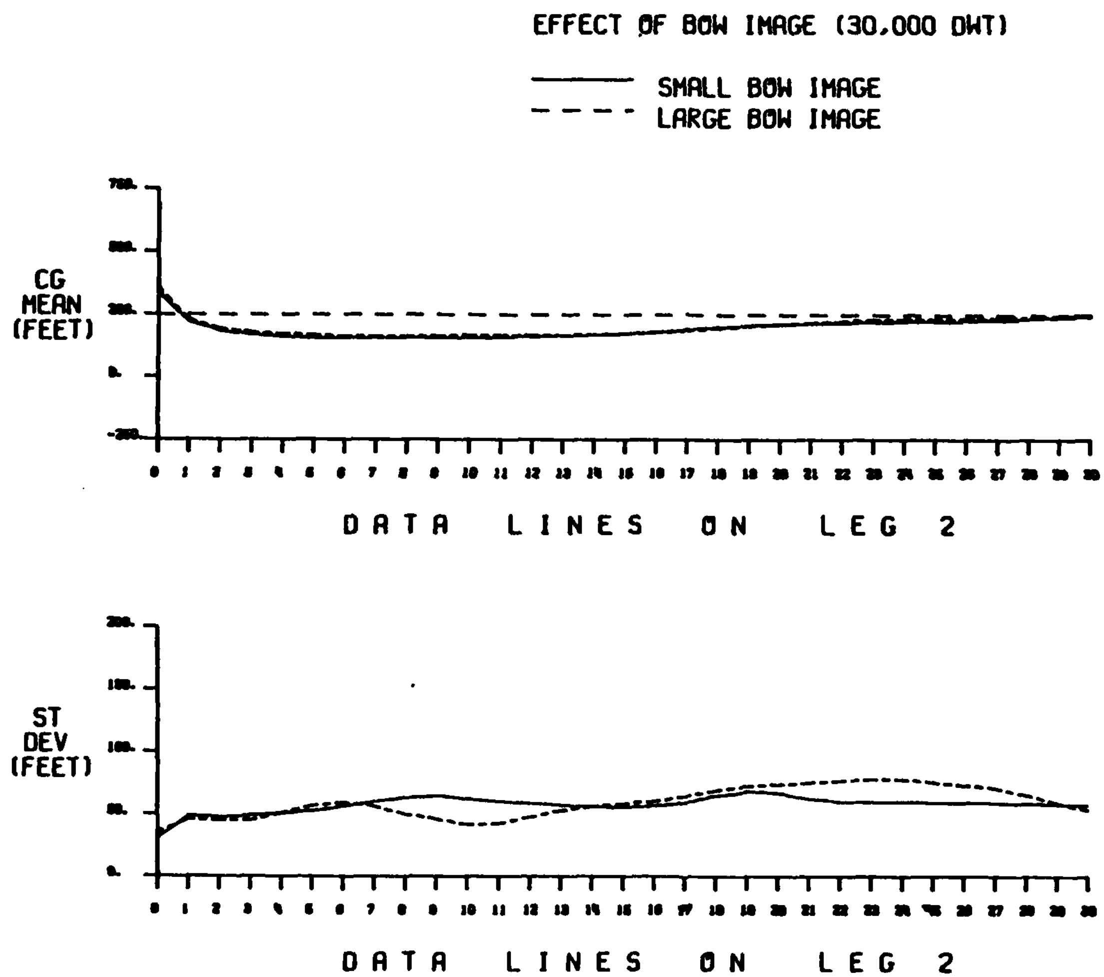

80,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 10 KTS
CG
MEAN
(FEET)
DATA LINES ON LEG 1
ST
DEV
(FEET)
DATA LINES ON LEG 1
CG
MEAN
+/-
2 ST DEV
(FEET)
DATA LINES ON LEG 1

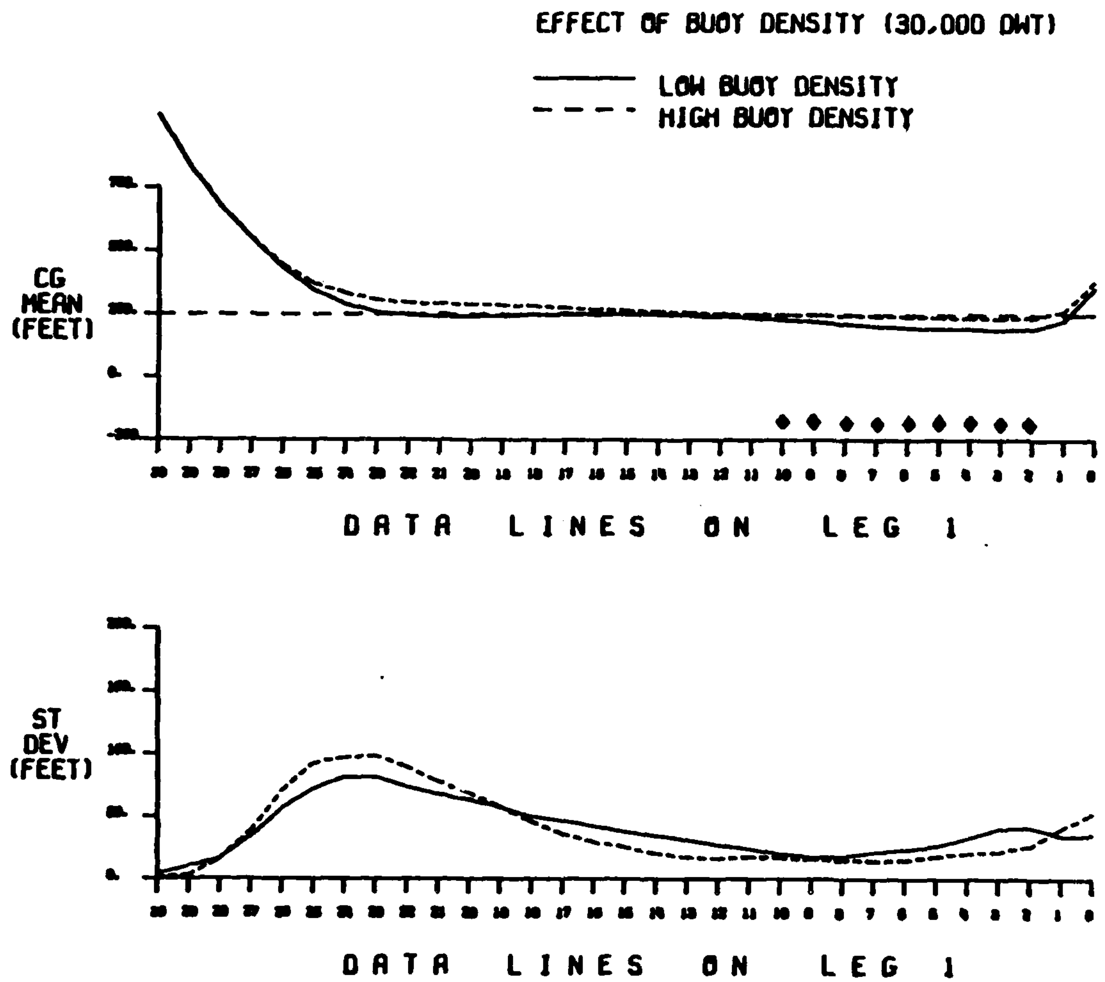
80,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 10 KTS

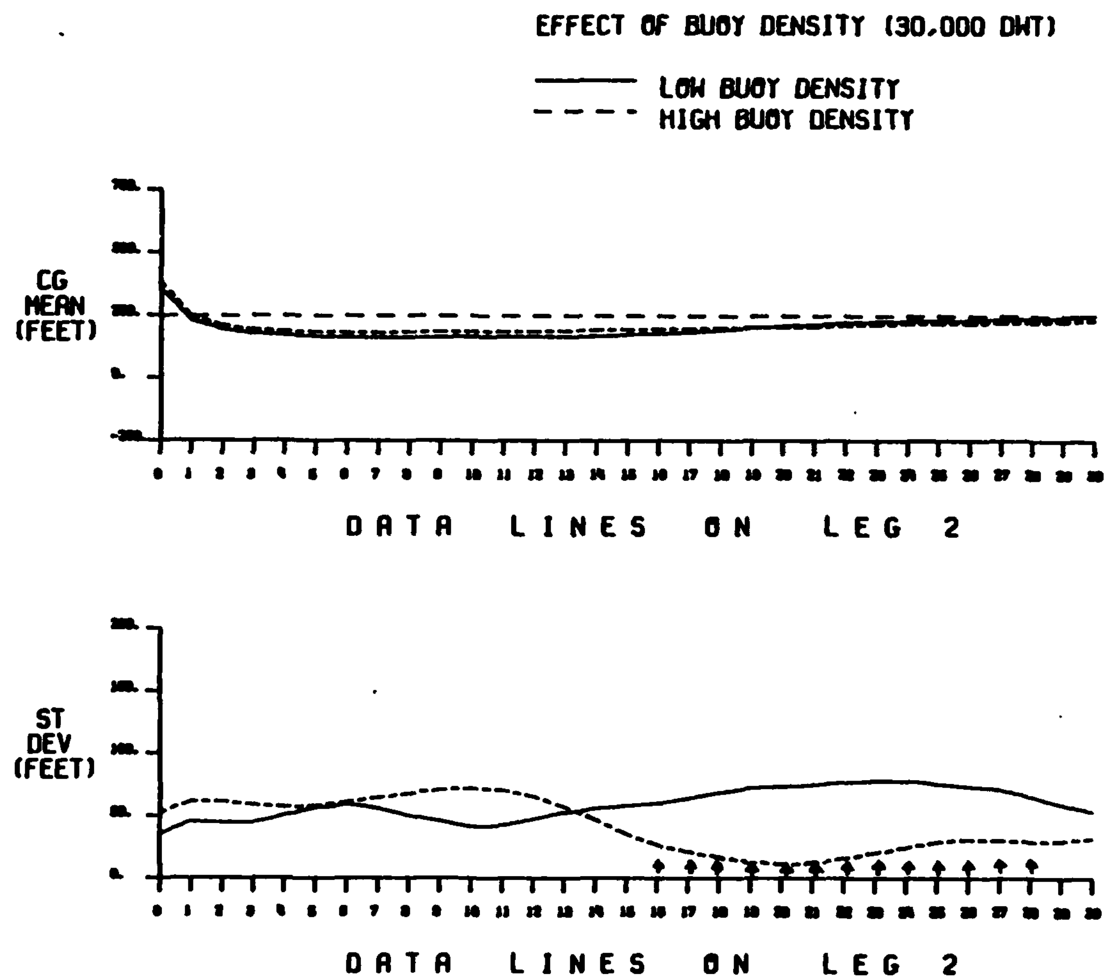


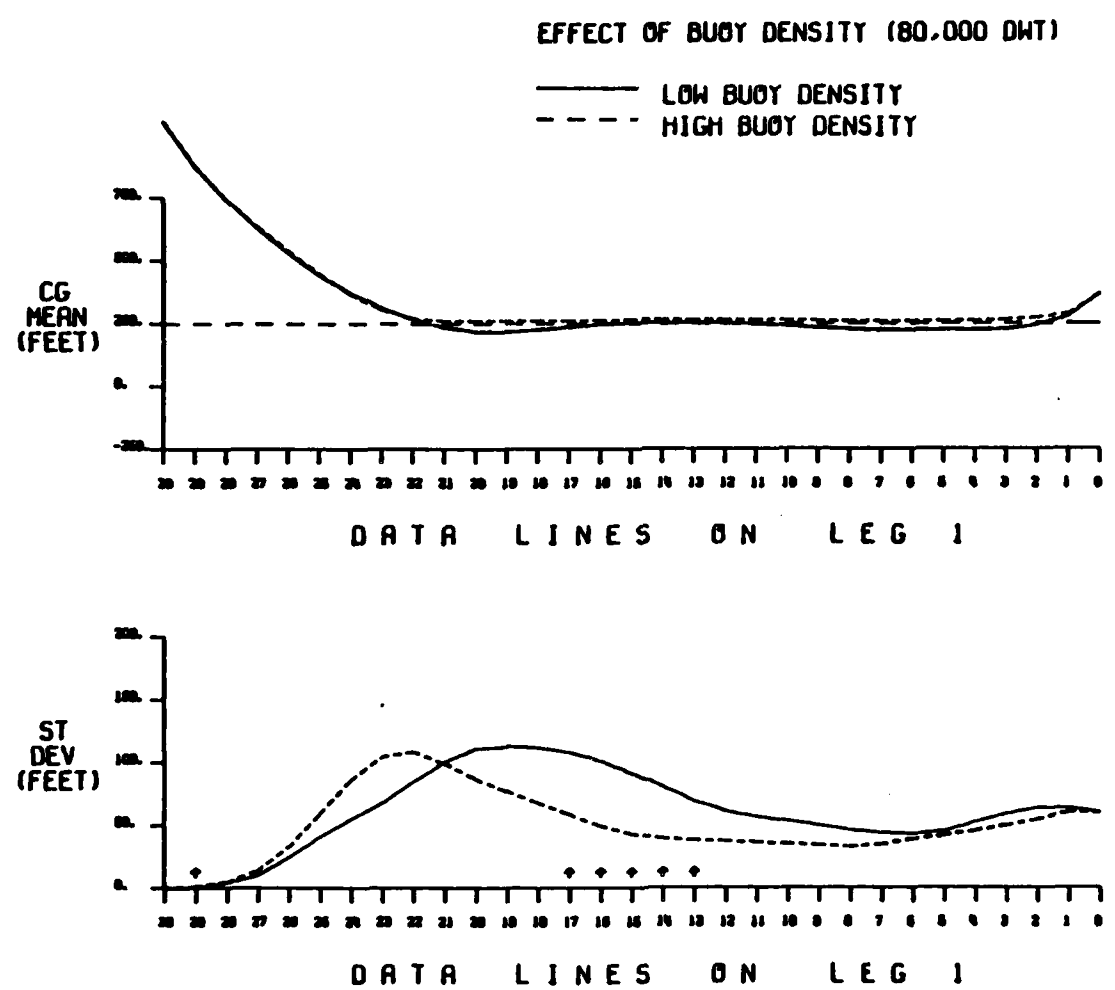


EFFECT OF BOW IMAGE (30,000 DWT)
SMALL BOW IMAGE
LARGE BOW IMAGE
CG
MEAN
(FEET)
DATA LINES ON LEG 1
ST
DEV
(FEET)
DATA LINES ON LEG 1

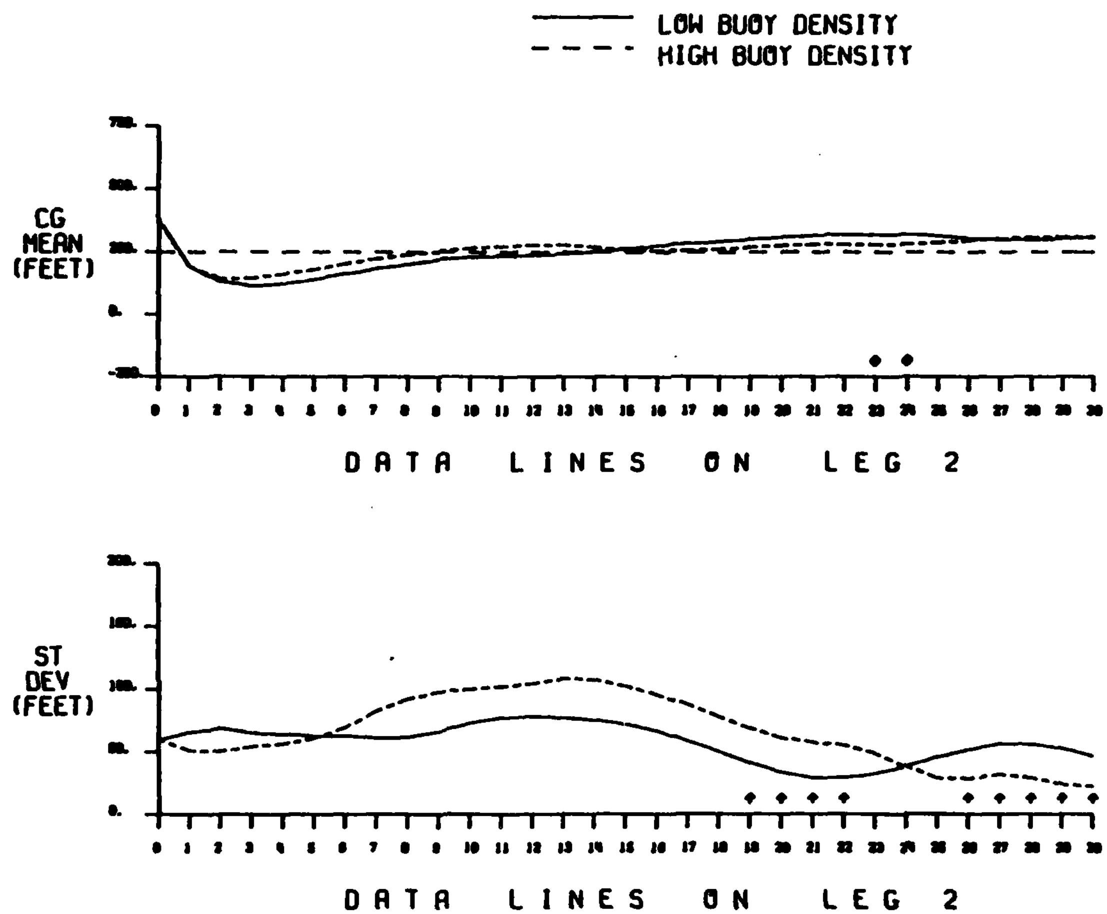

EFFECT OF BOW IMAGE (30,000 DWT)
SMALL BOW IMAGE
LARGE BOW IMAGE
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2

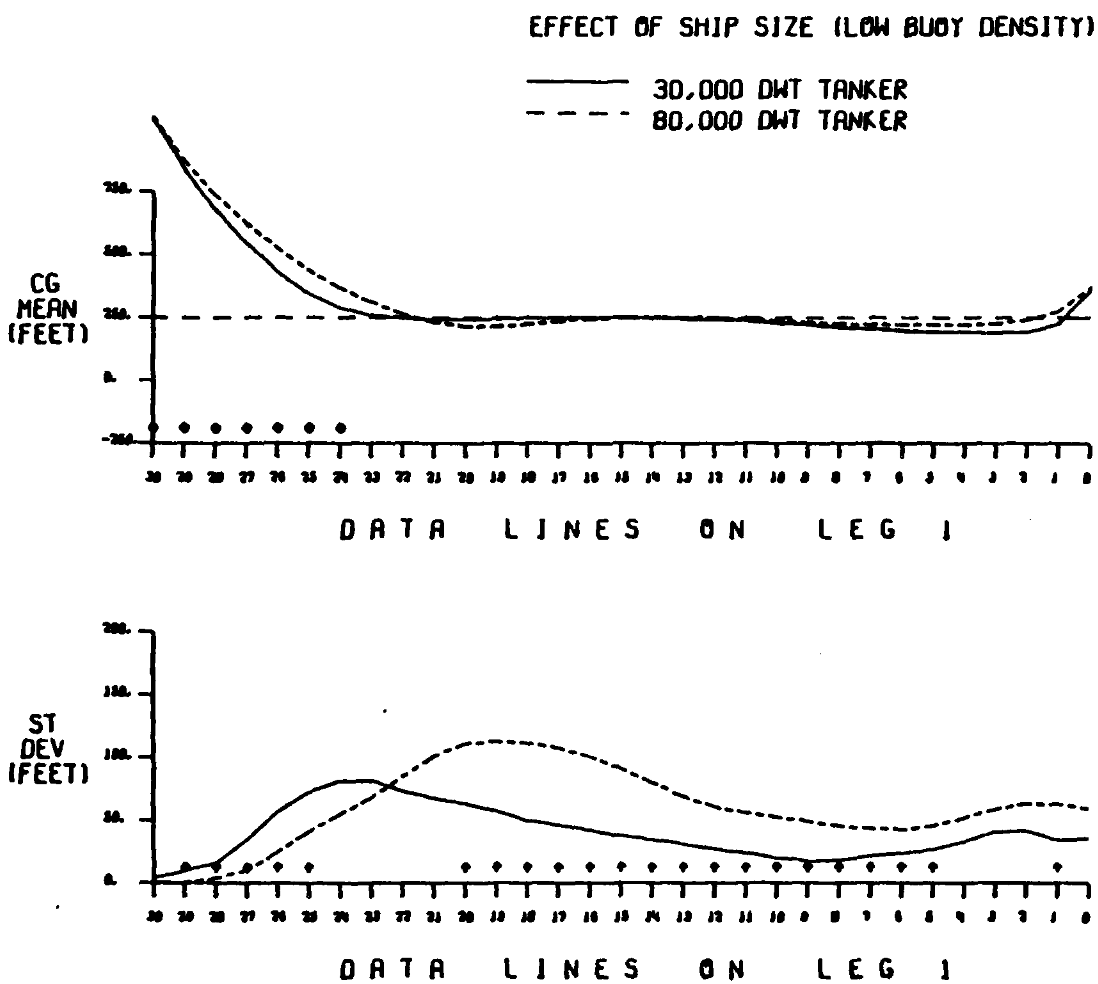

EFFECT OF BUOY DENSITY (30,000 DWT)
LOW BUOY DENSITY
HIGH BUOY DENSITY
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1

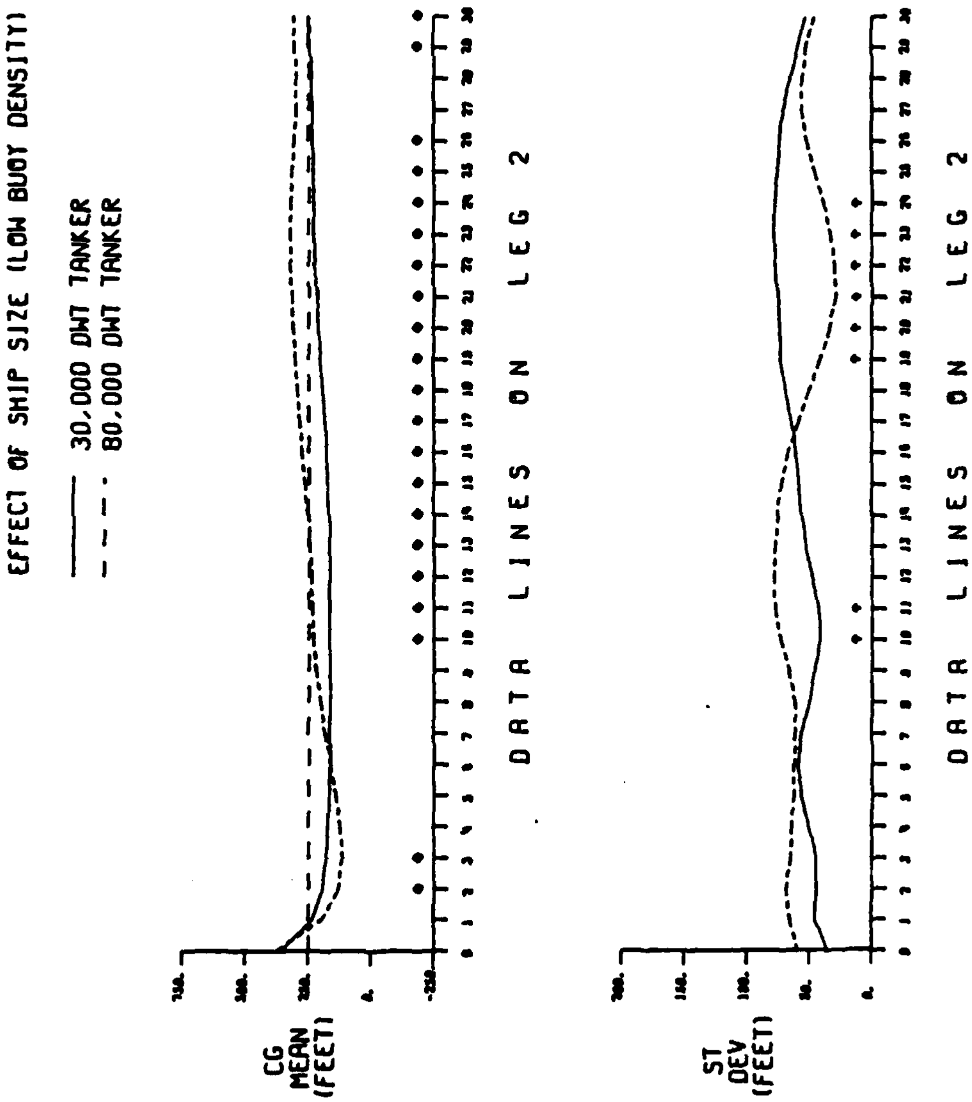

EFFECT OF BUOY DENSITY (30,000 DWT)
LOW BUOY DENSITY
HIGH BUOY DENSITY
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2


EFFECT OF BUOY DENSITY (80,000 DWT)
LOW BUOY DENSITY
HIGH BUOY DENSITY
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1

EFFECT OF BUOY DENSITY (80,000 DWT)

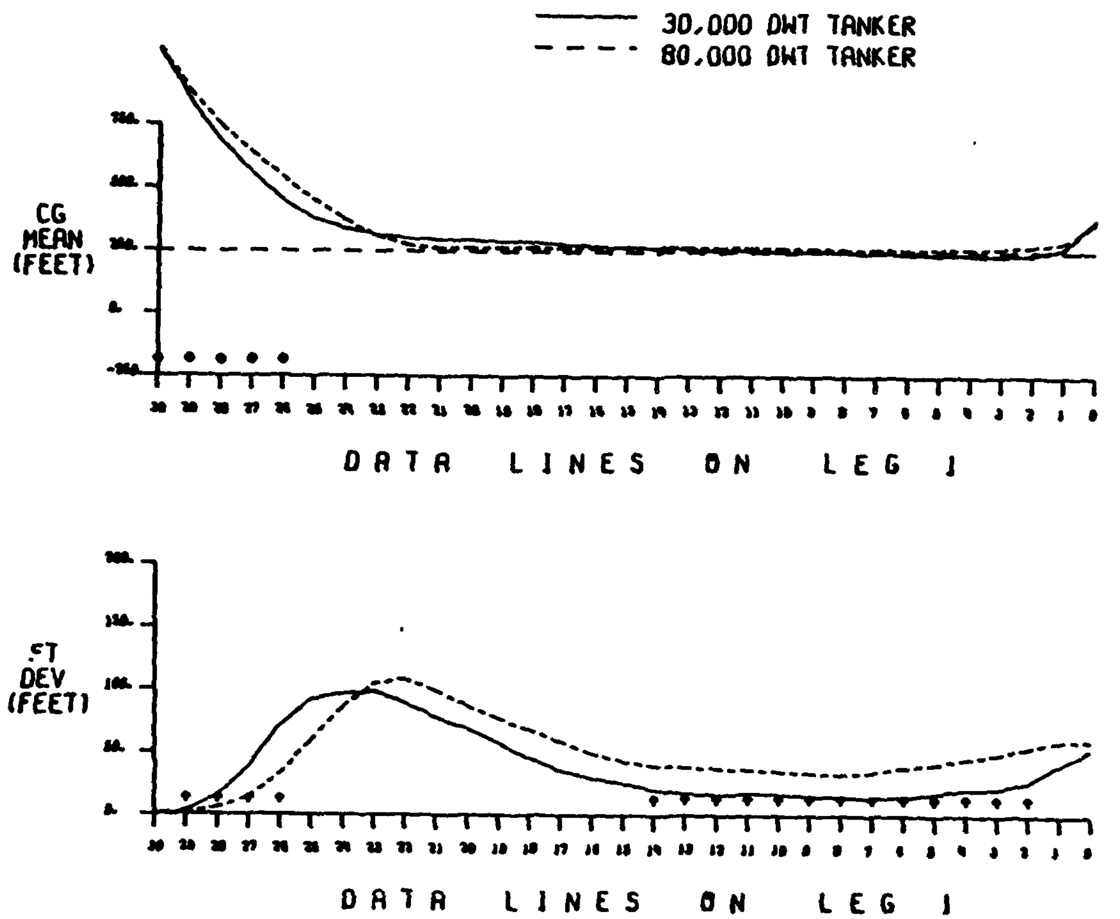



EFFECT OF SHIP SIZE (LOW BUOY DENSITY)
30,000 DWT TANKER
80,000 DWT TANKER
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1

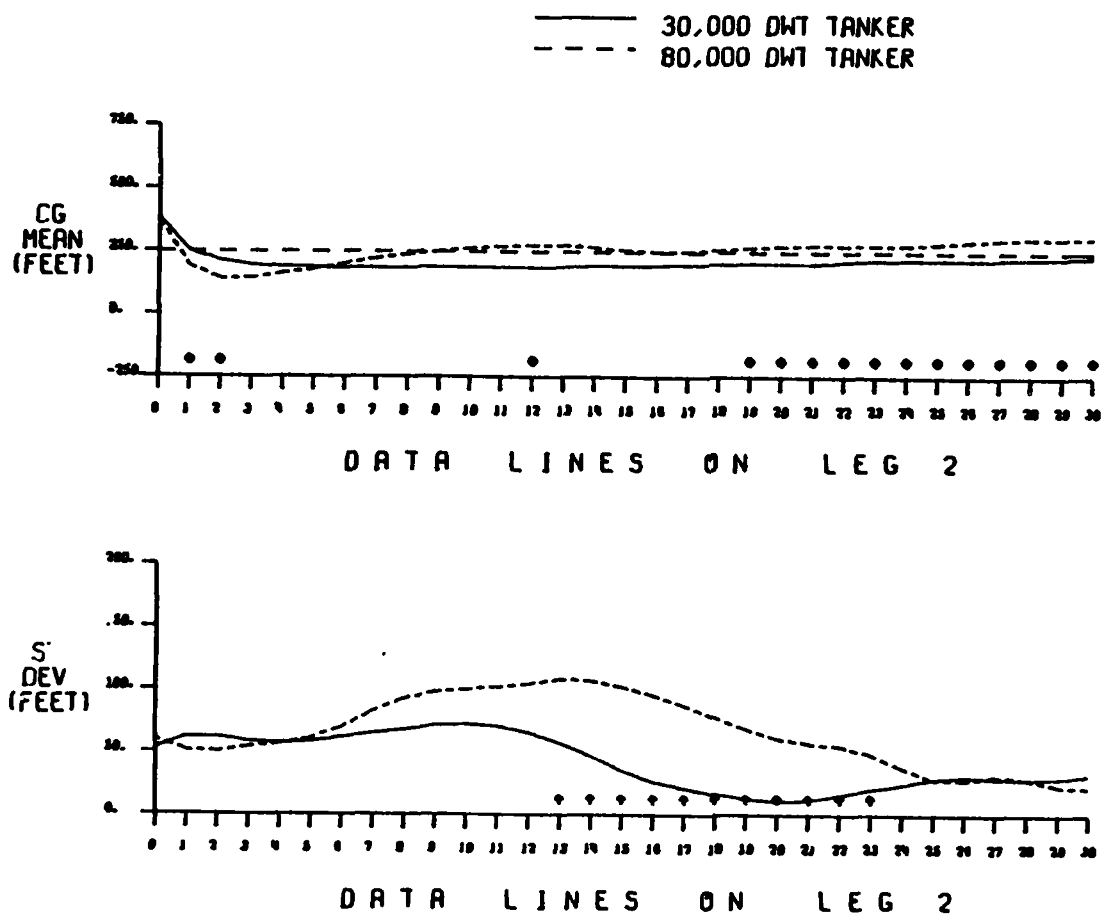


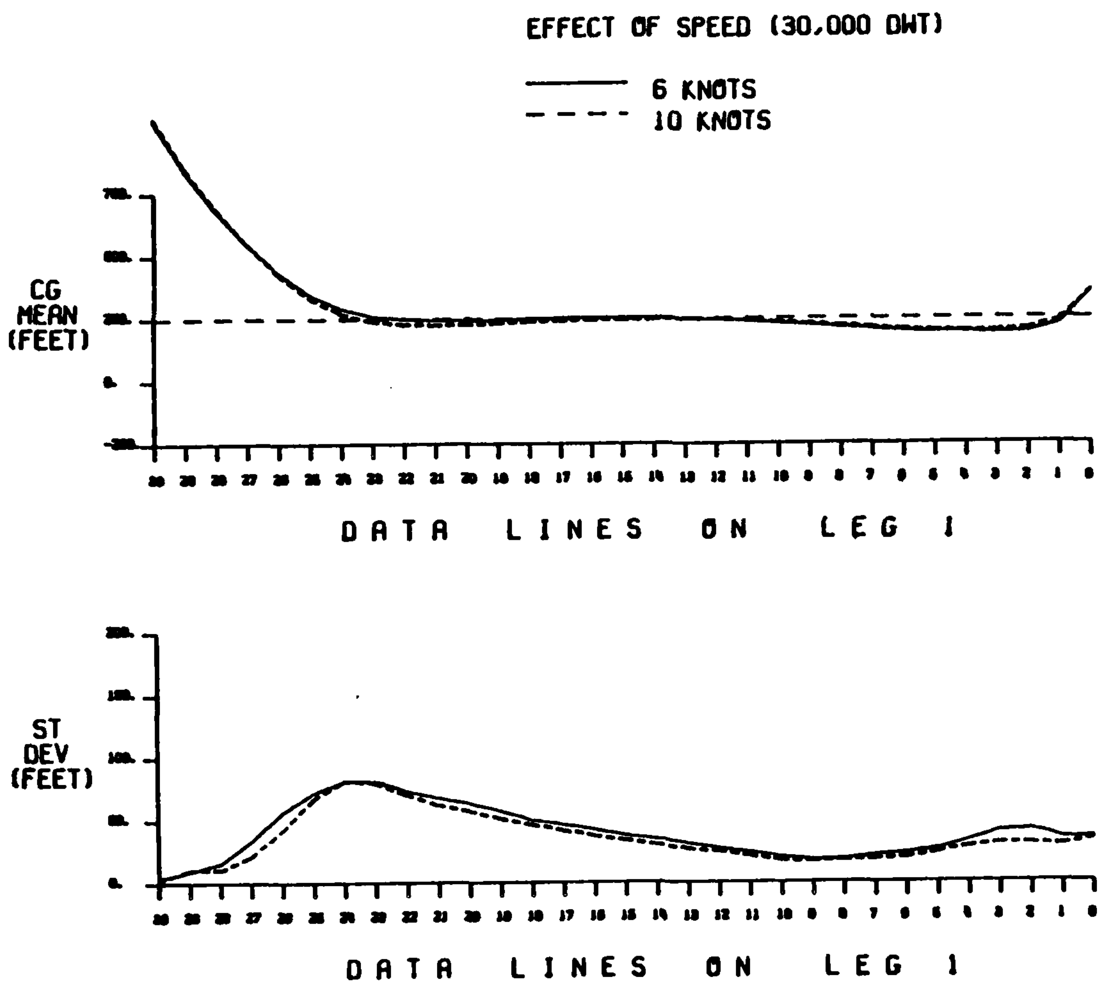
EFFECT OF SHIP SIZE (LOW BUOY DENSITY)
30,000 DWT TANKER
80,000 DWT TANKER
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2

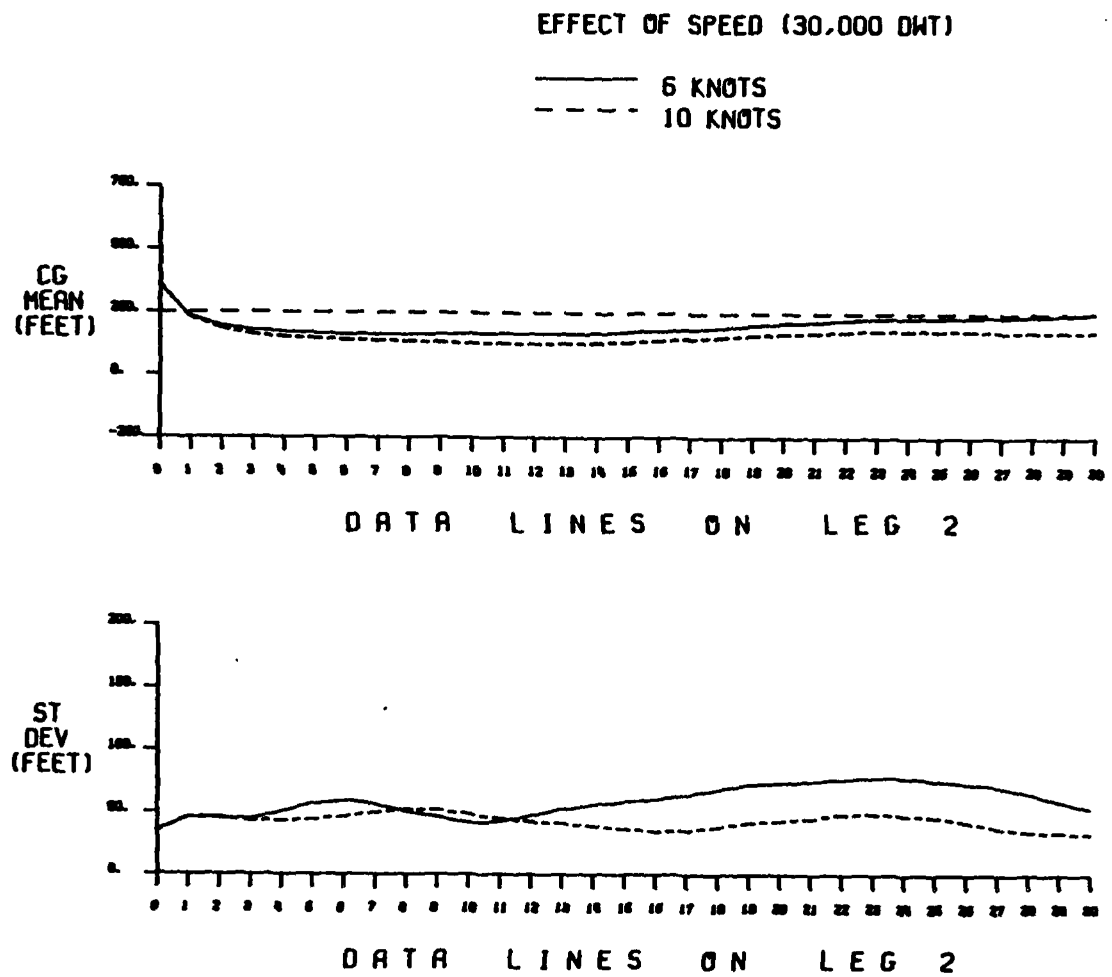
EFFECT OF SHIP SIZE (HIGH BUOY DENSITY)



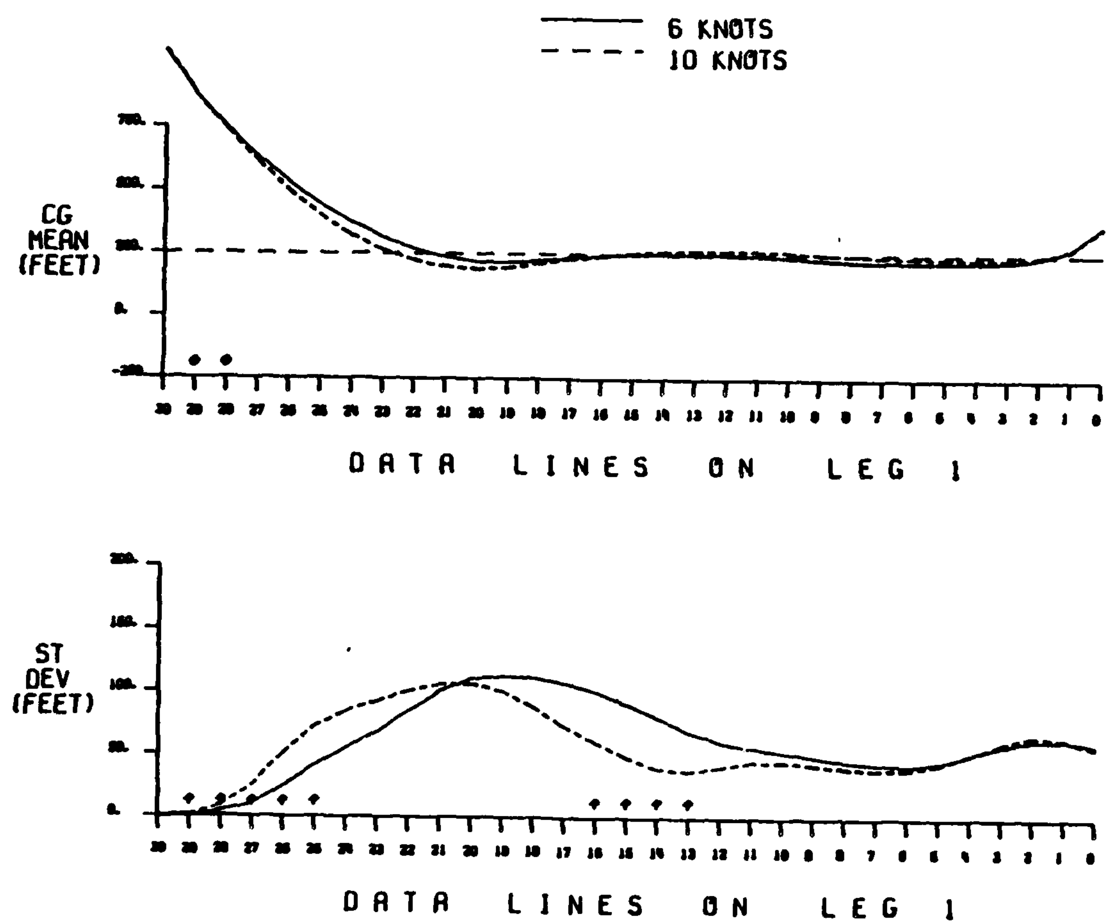
EFFECT OF SHIP SIZE (HIGH BUOY DENSITY)

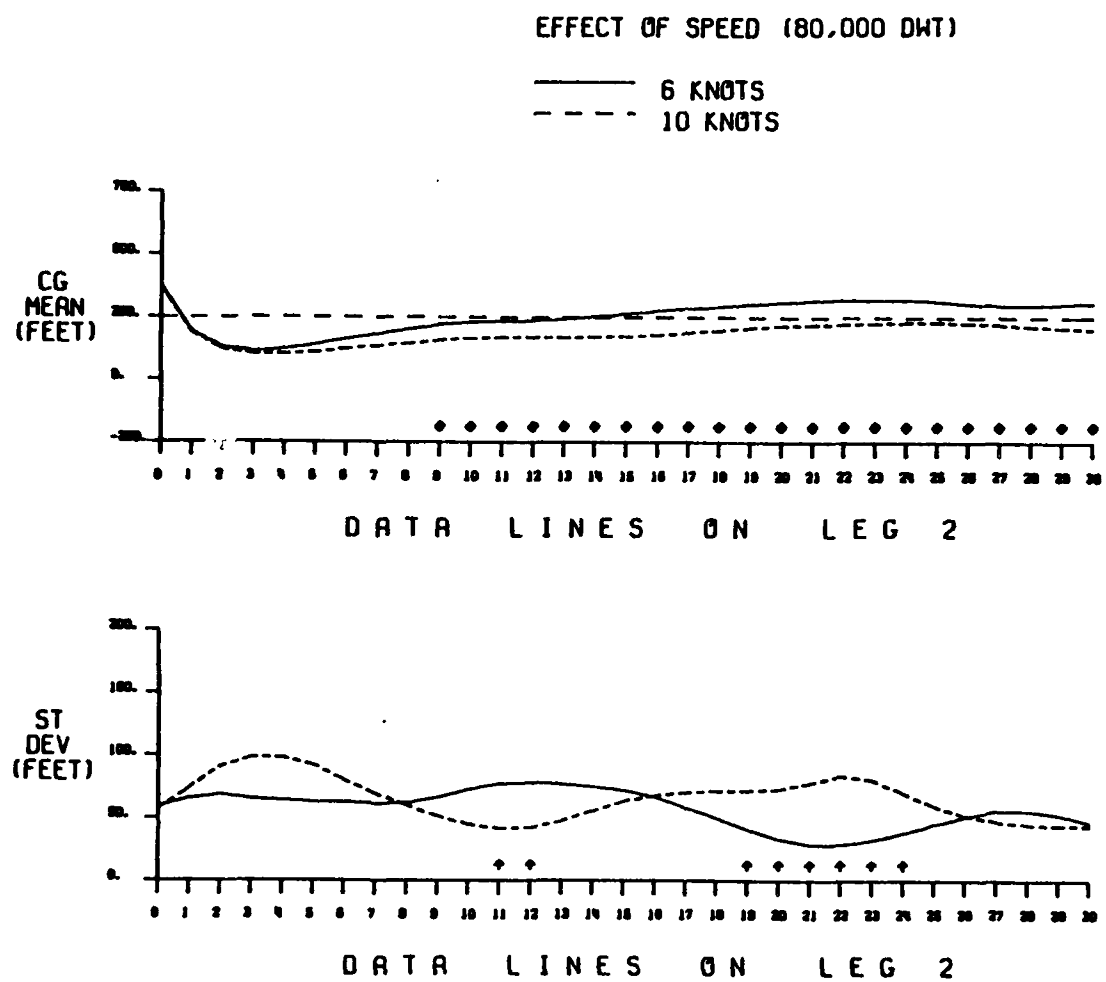


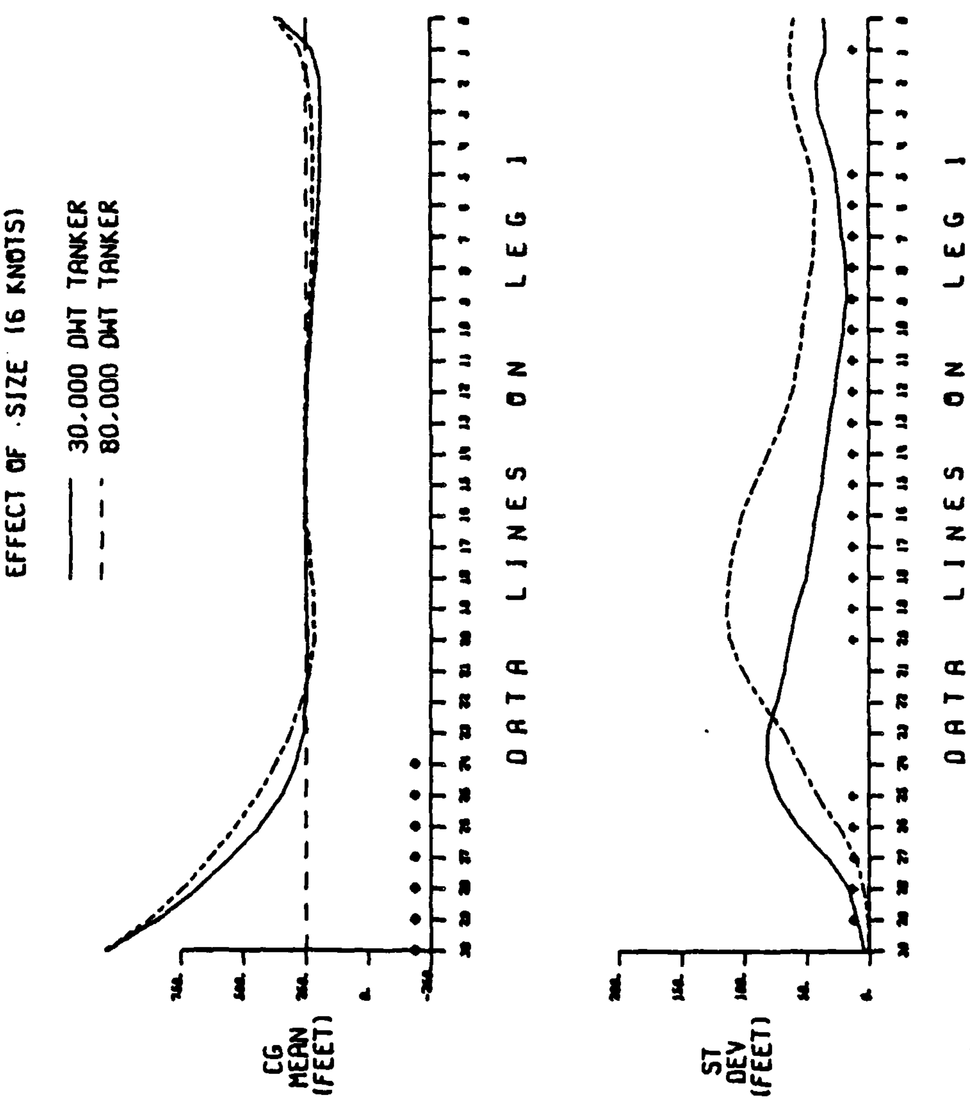

EFFECT OF SPEED (30,000 DWT)
6 KNOTS
10 KNOTS
CG
MEAN
(FEET)
DATA LINES ON LEG 1
ST
DEV
(FEET)
DATA LINES ON LEG 1

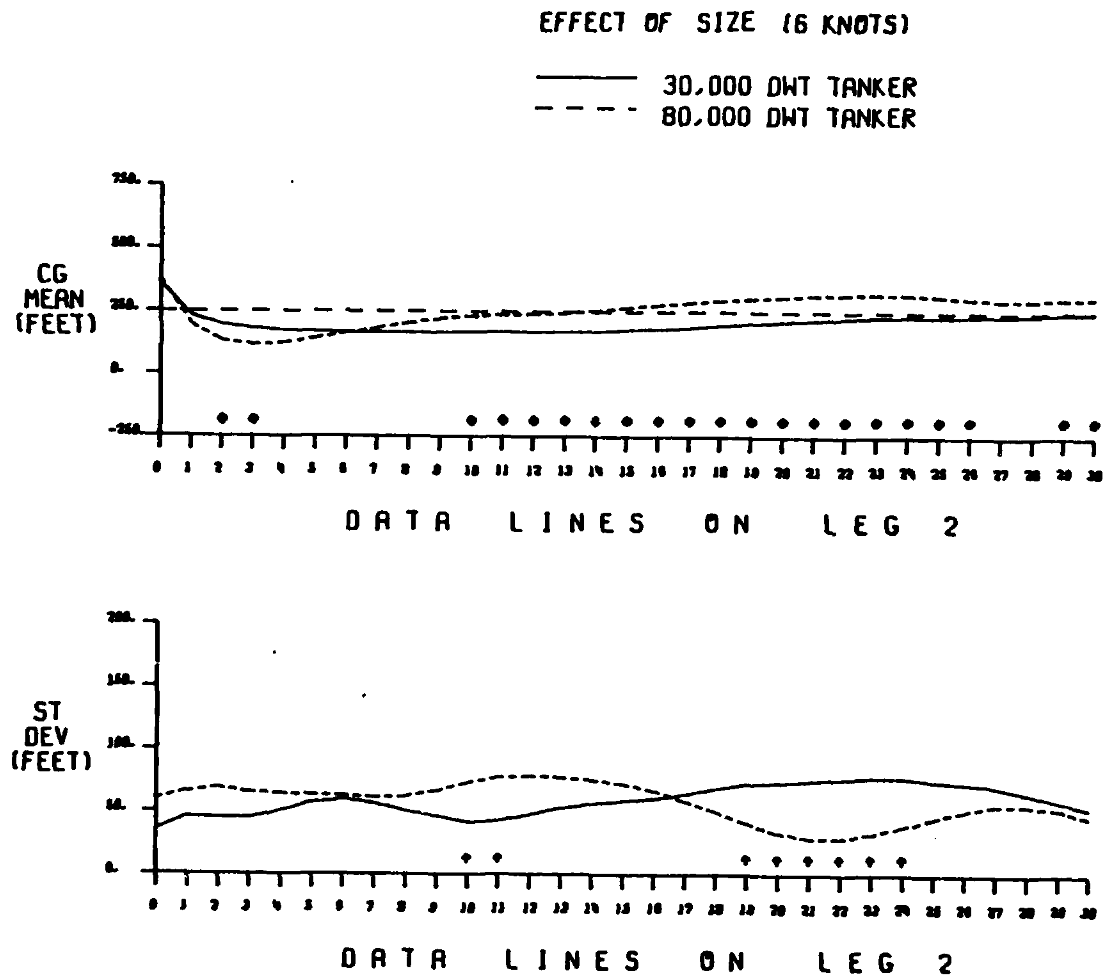

EFFECT OF SPEED (30,000 DWT)
6 KNOTS
10 KNOTS
CG
MEAN
(FEET)
DATA LINES ON LEG 2
ST
DEV
(FEET)
DATA LINES ON LEG 2

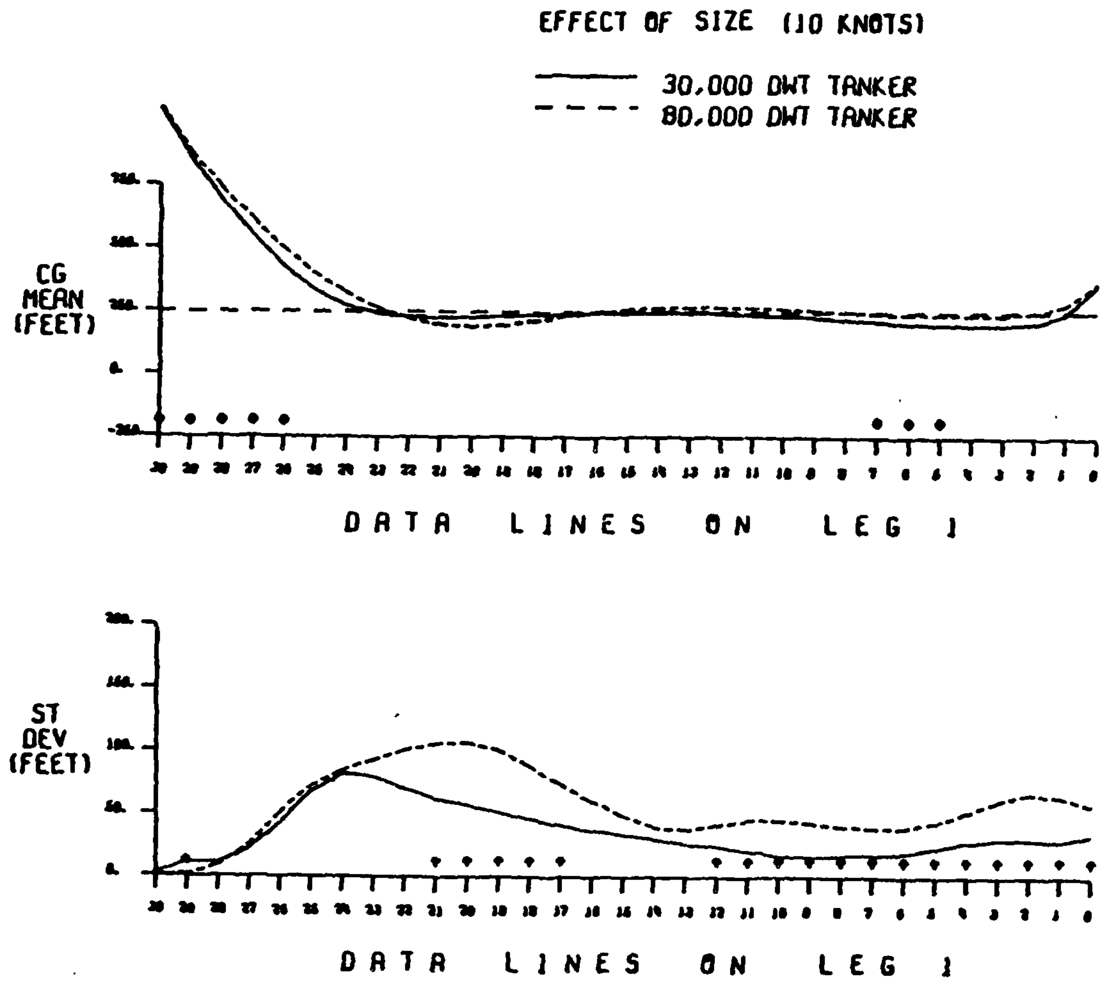
EFFECT OF SPEED (80,000 DWT)

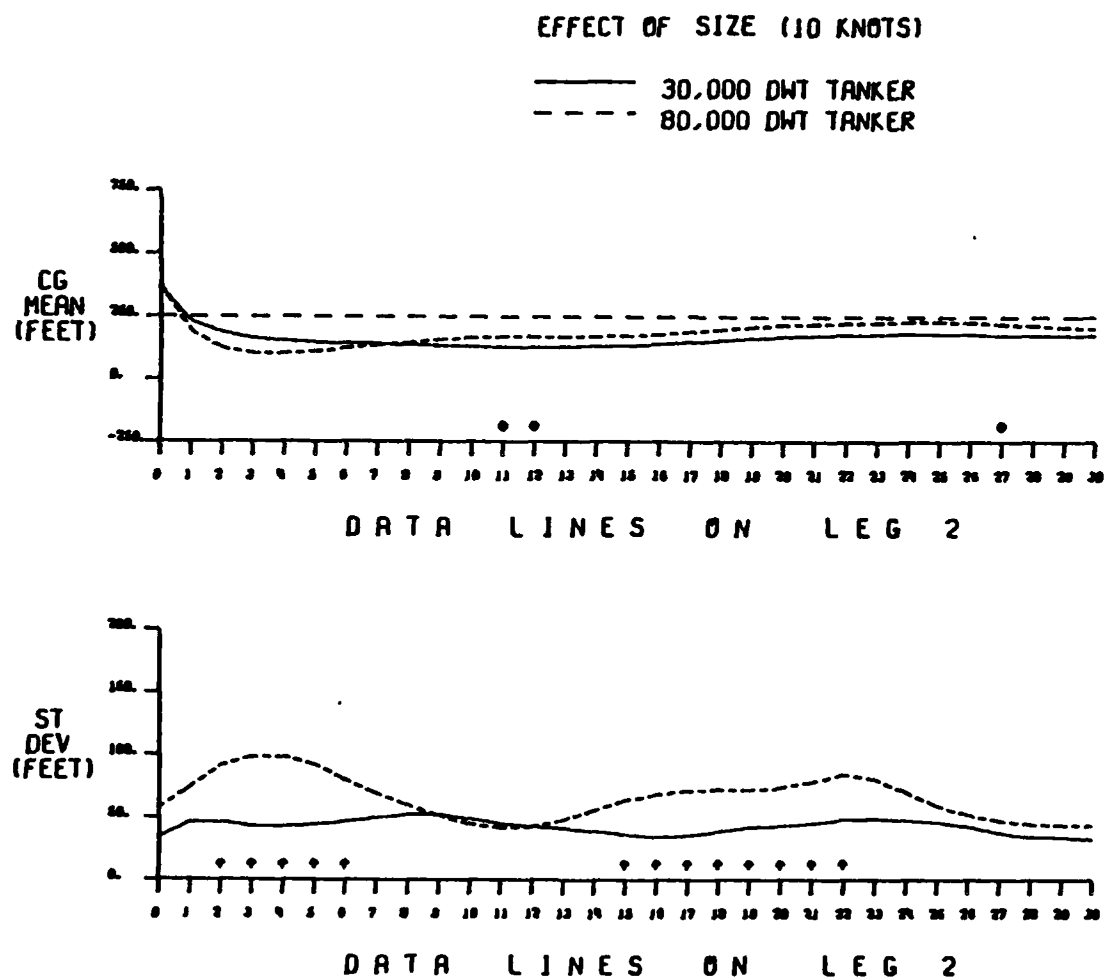


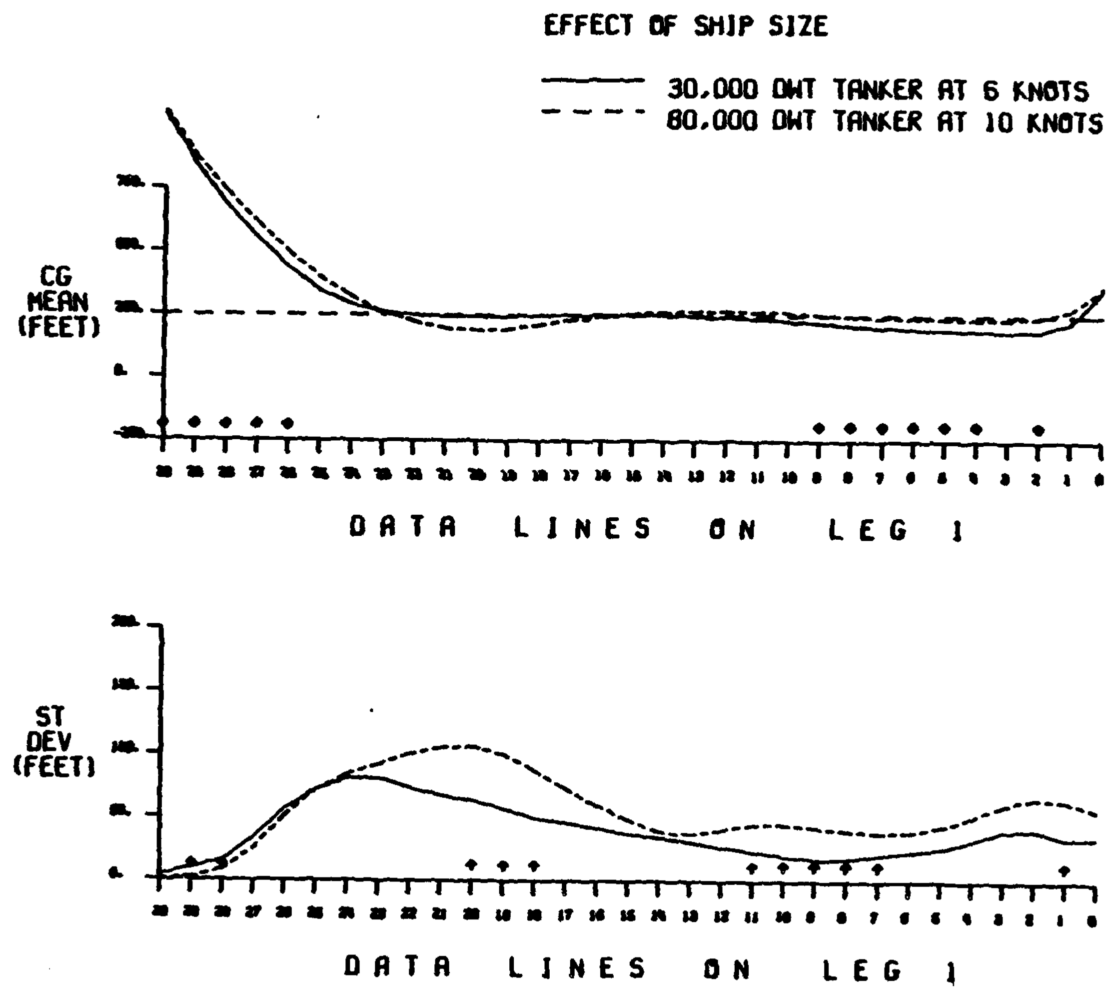

EFFECT OF SPEED (80,000 DWT)
6 KNOTS
10 KNOTS
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2


EFFECT OF SIZE (6 KNOTS)
30,000 DWT TANKER
80,000 DWT TANKER
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1

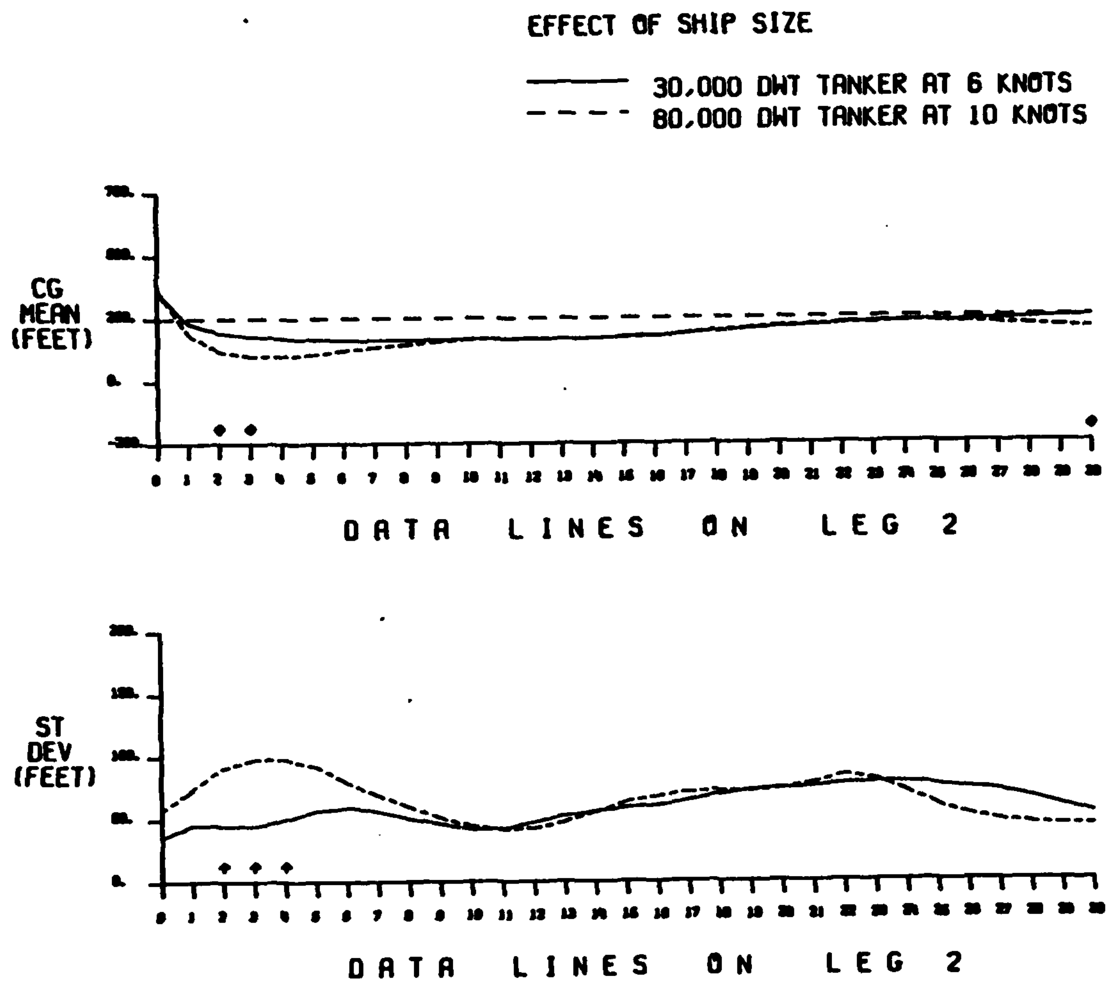

EFFECT OF SIZE (6 KNOTS)
30,000 DWT TANKER
80,000 DWT TANKER
CG
MEAN
(FEET)
DATA LINES ON LEG 2
ST
DEV
(FEET)
DATA LINES ON LEG 2


EFFECT OF SIZE (10 KNOTS)
30,000 DWT TANKER
80,000 DWT TANKER
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1

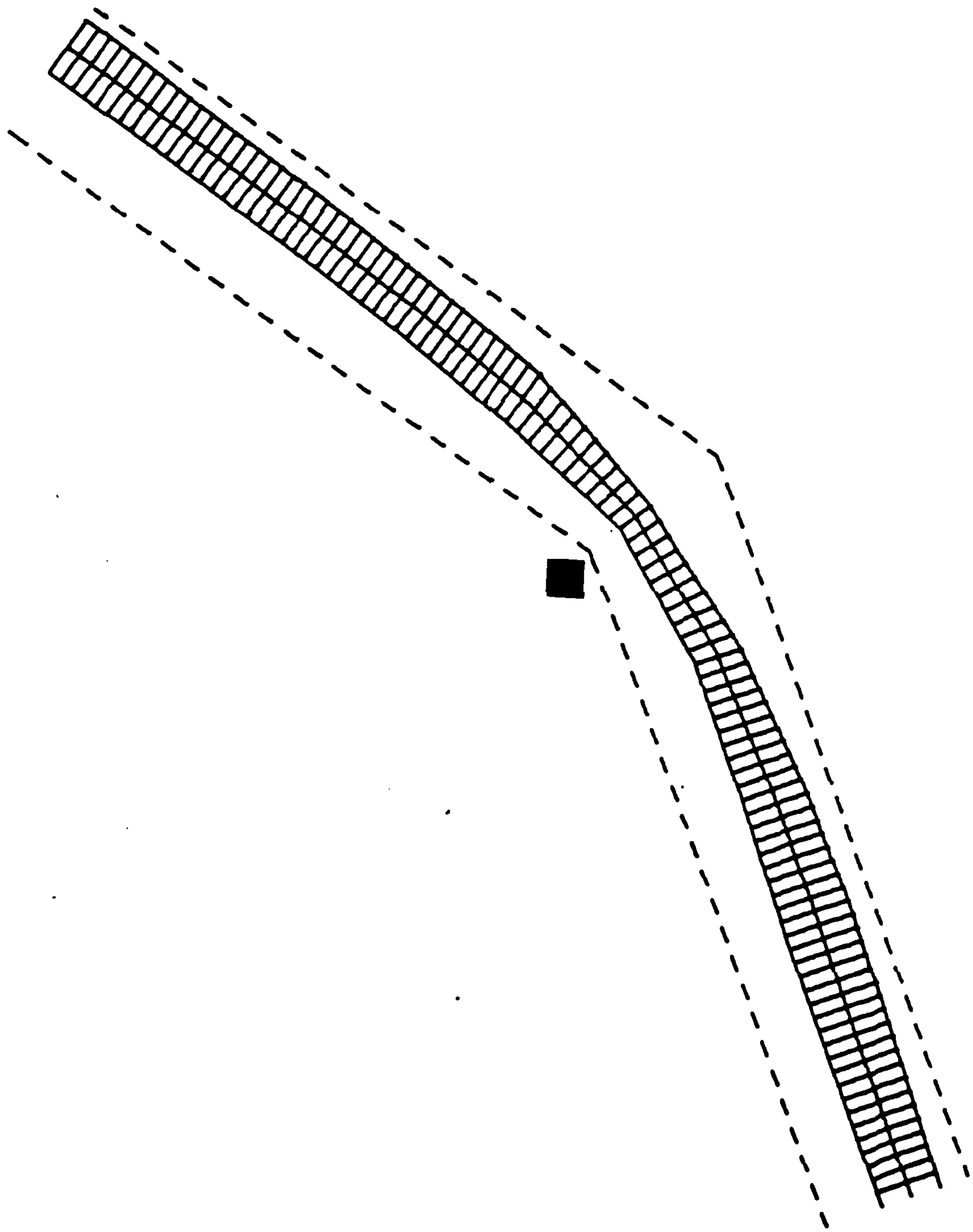

EFFECT OF SIZE (10 KNOTS)
30,000 DWT TANKER
80,000 DWT TANKER
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2



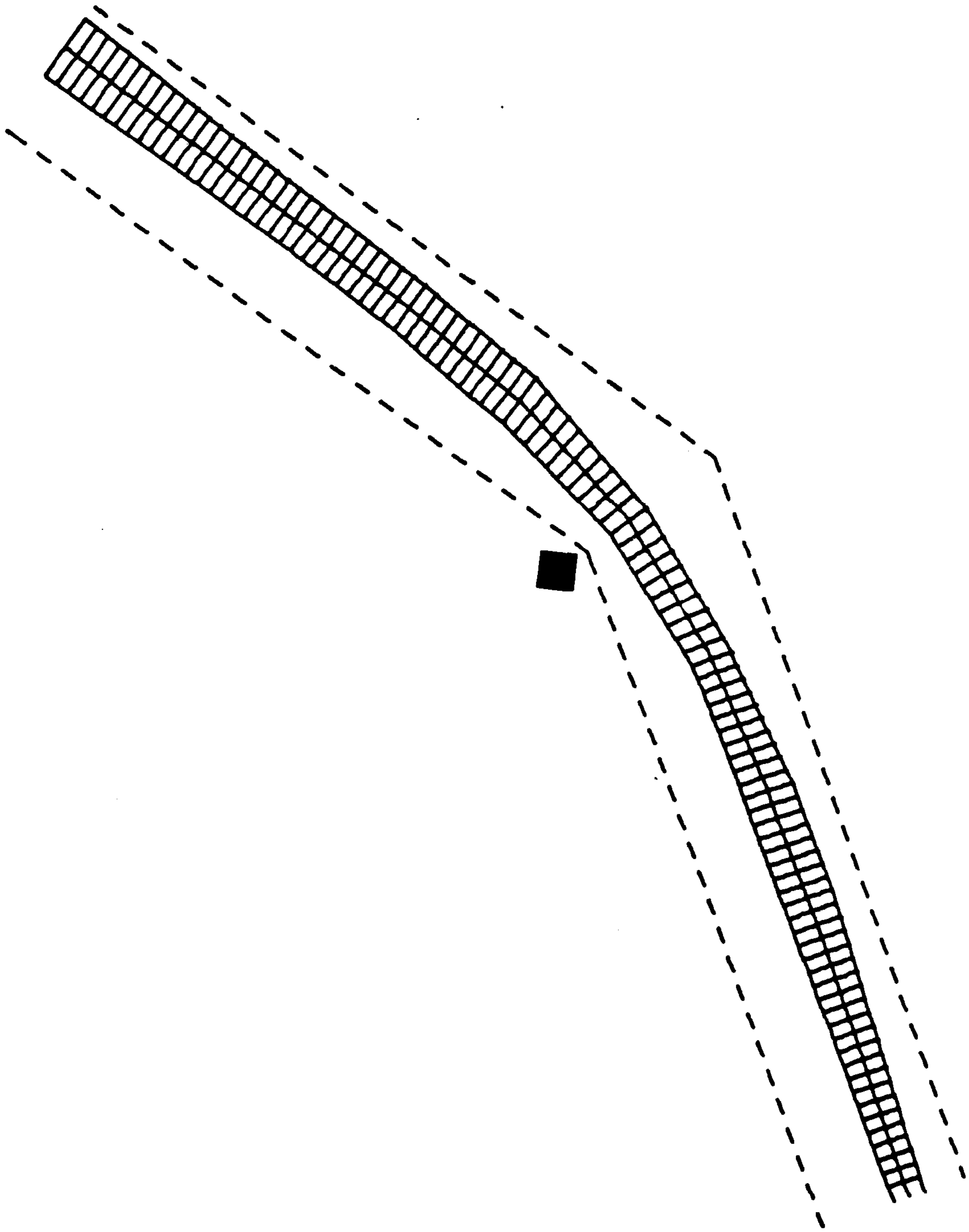
EFFECT OF SHIP SIZE
30,000 DWT TANKER AT 6 KNOTS
80,000 DWT TANKER AT 10 KNOTS
CG MEAN (FEET)
DATA LINES ON LEG 1
ST DEV (FEET)
DATA LINES ON LEG 1


EFFECT OF SHIP SIZE
30,000 DWT TANKER AT 6 KNOTS
80,000 DWT TANKER AT 10 KNOTS
CG MEAN (FEET)
DATA LINES ON LEG 2
ST DEV (FEET)
DATA LINES ON LEG 2

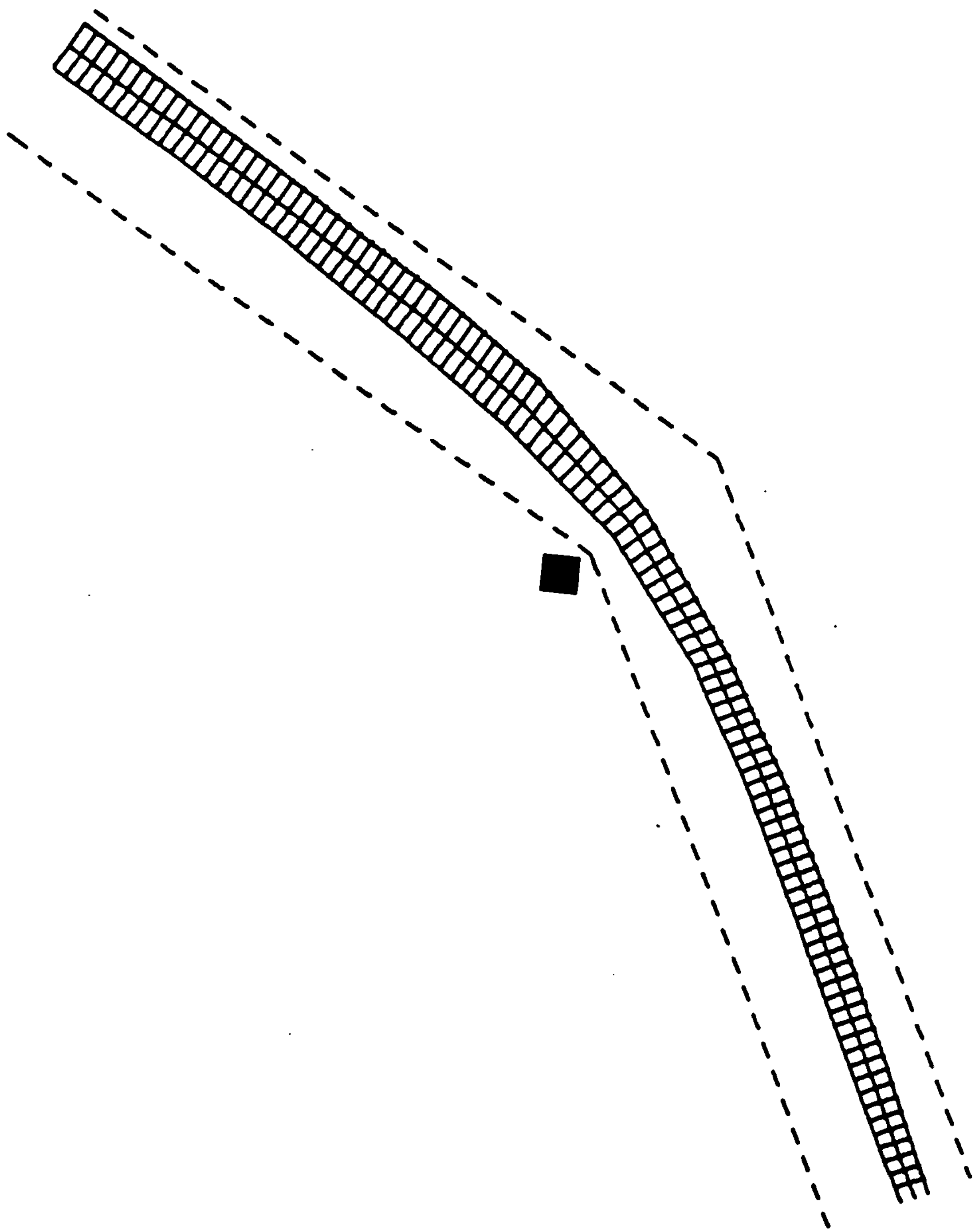
30,000 DWT TANKER - SMALL BOW - STAGGERED BUOYS - 6 KTS



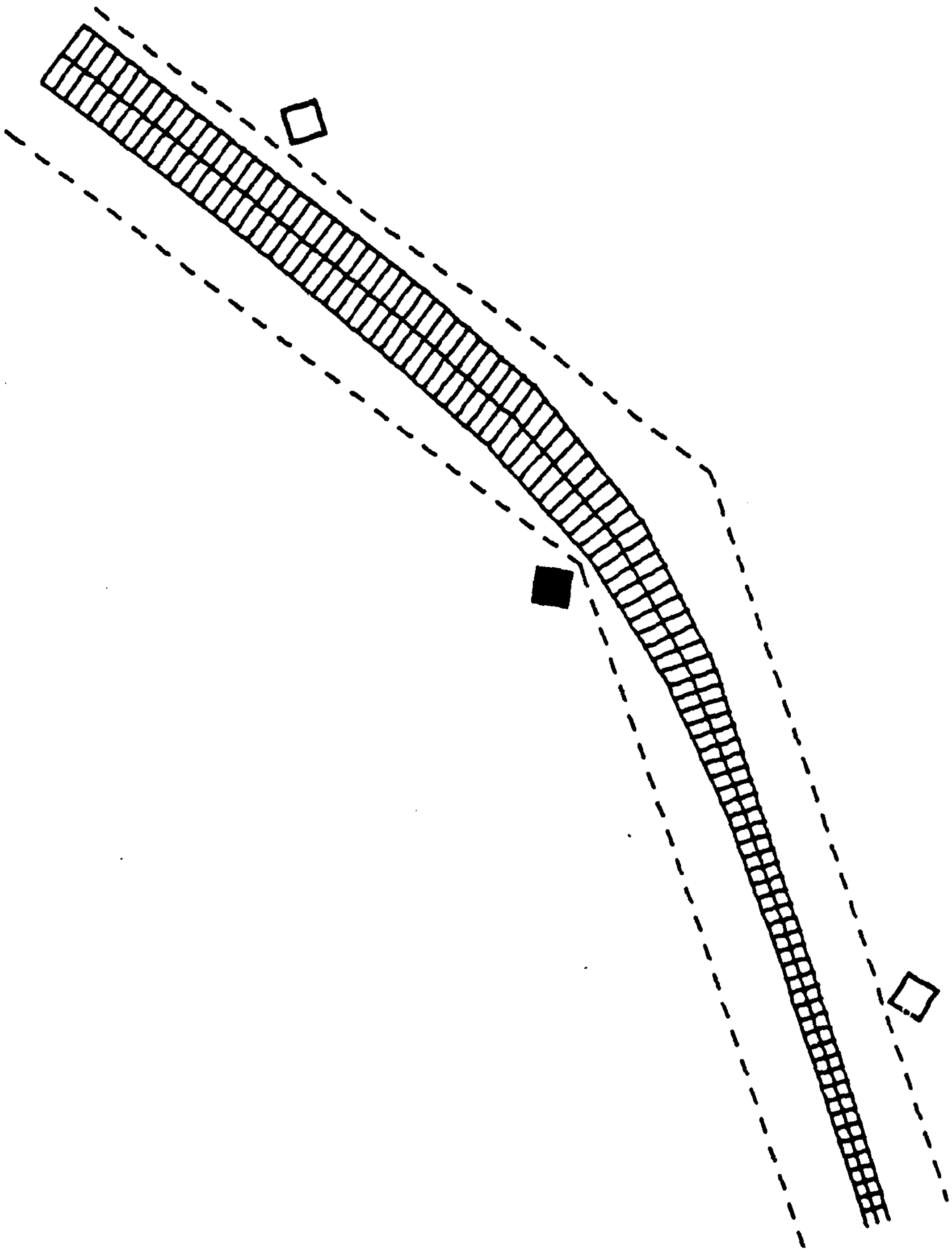
30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS - 6 KTS



30,000 DWT TANKER -LARGE BOW- STAGGERED BUOYS -10 KTS



30,000 DWT TANKER -LARGE BOW- GATED BUOYS -6 KTS



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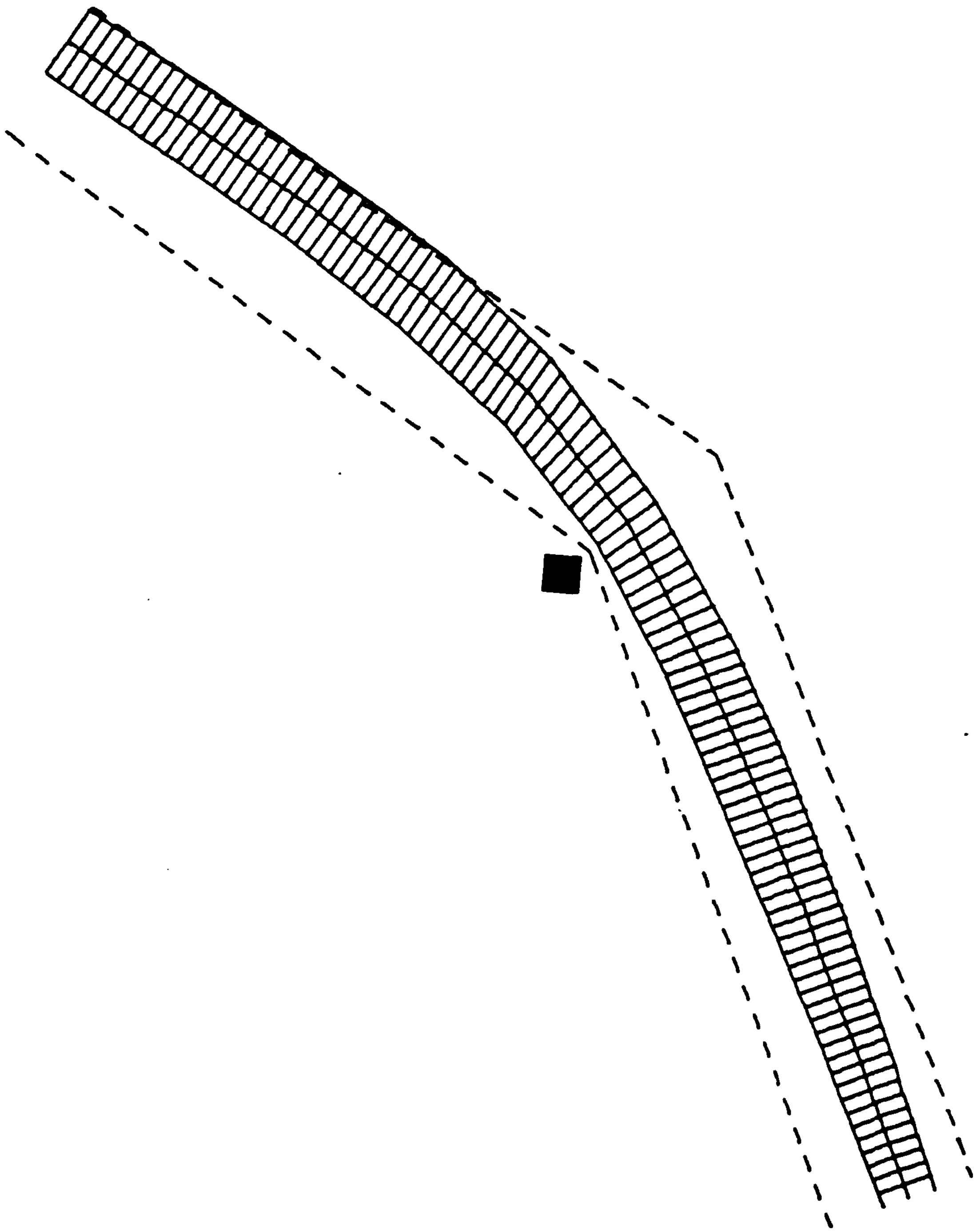

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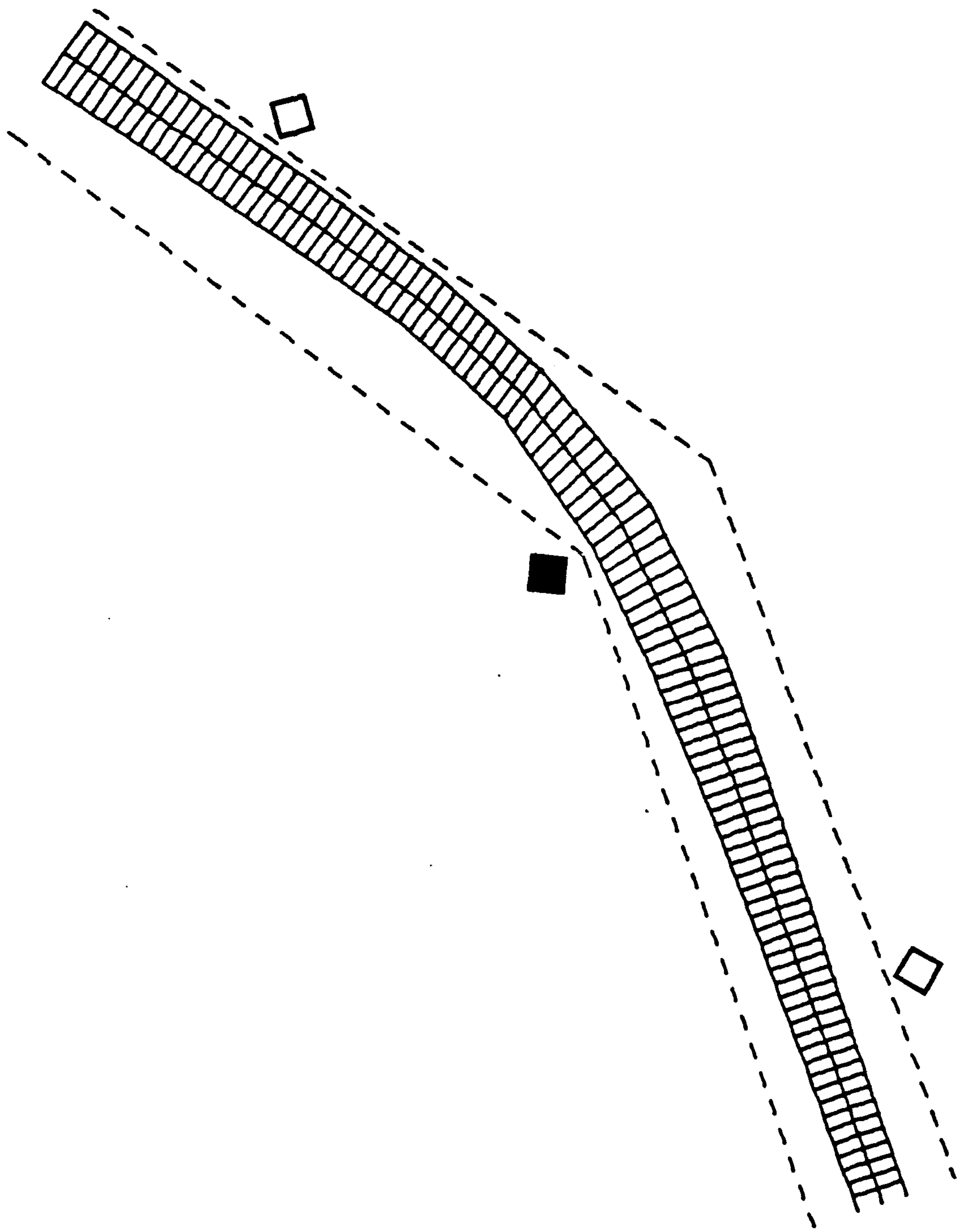

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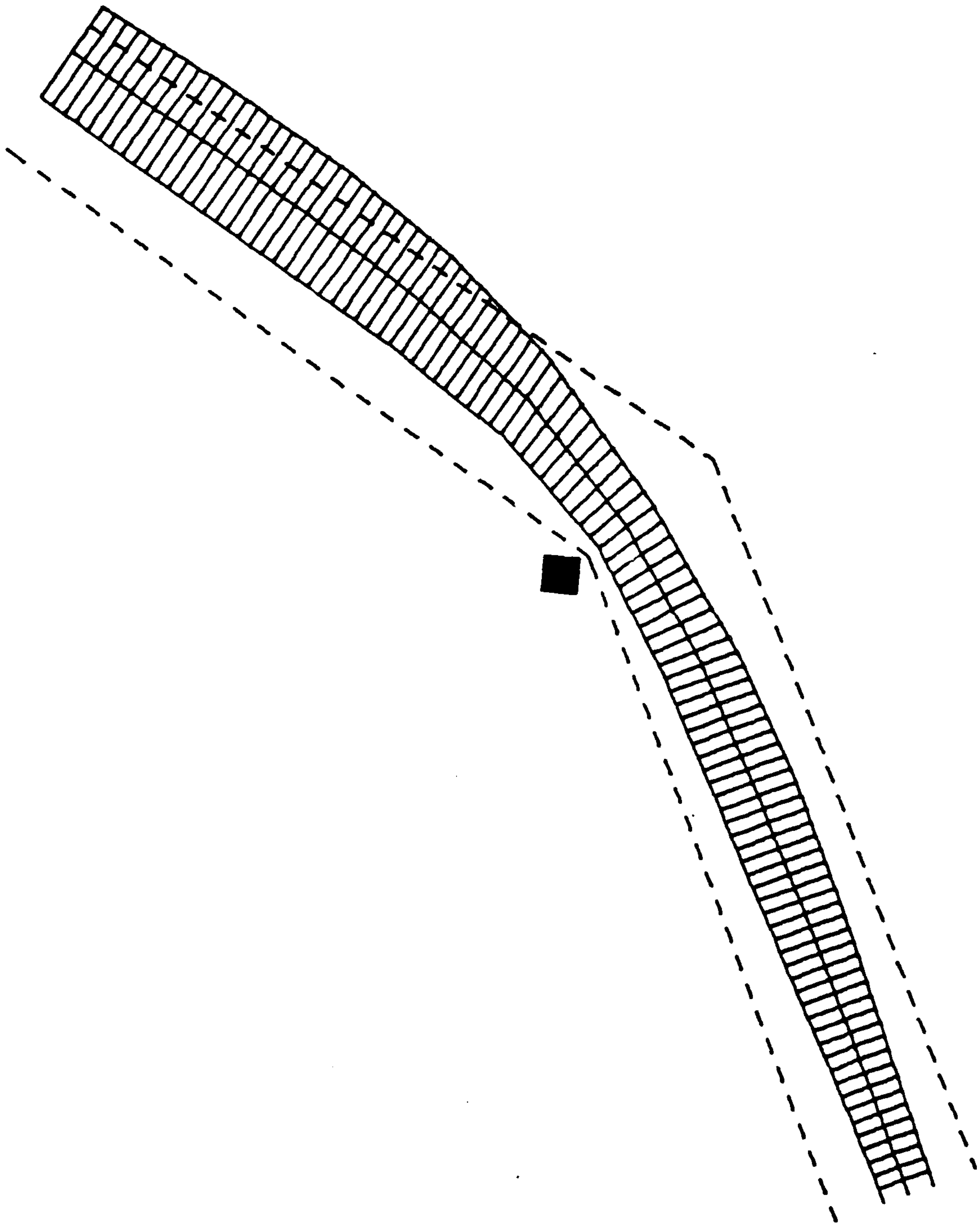

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AIDS TO NAVIGATION PRINCIPAL FINDINGS REPORT ON THE SHIP VARIAB--ETC(U)
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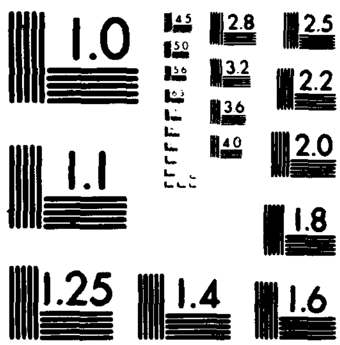

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